Additive Manufacturing (3D Printing) Aircraft Parts and Tooling at the Maintenance Group Level

Graduate Research Paper

Michael J. Thompson, Major, USAF

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ADDITIVE MANUFACTURING (3D PRINTING) AIRCRAFT PARTS AND TOOLING AT THE MAINTENANCE GROUP LEVEL

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Abstract

The purpose of this research was to evaluate the effectiveness of additive manufacturing (AM) or 3D printing for the Air Force's aircraft maintenance community and determine if the technology is applicable for use at the Maintenance Group (MXG) level. Specifically, this paper sought to answer two pivotal questions, addressing if AM is mature enough to produce any viable aircraft components for use and if so, prove the concept by printing an aircraft part. Research uncovered the 552d MXG at Tinker Air Force Base, Oklahoma effort's to create difficult to procure aircraft parts and tooling using a 3D printer. A case study of the 552d MXG's 3D printing operation explores their use of a Fused Deposition Modeling (FDM) thermoplastic material to manufacture potential aircraft parts at the squadron level.

This paper also explored recent innovations and methodologies used in AM within industry. The research continued by applying the case study's analysis toward a proof of concept, producing a C-130J Aft Cargo Door Rub Strip for 3D printing. The study concluded by presenting a recommendation to field 3D printing suites for aircraft maintenance units to leverage AM as an alternate source for aircraft parts and tooling.

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To my family, your love and unwavering support is my inspiration. Thank you….143.

Acknowledgments

I would like to thank several contributors to the successful completion of this research. Thank you to the 552d Maintenance Group (MXG) for their access and hosting me within their unit. It was your innovation which propelled this paper after I hit numerous roadblocks in the months before our meeting. Specifically, I would like to thank Major Paul Weme for allowing me to run around his squadron for the visit. To SMSgt Bradley Green for ushering me around, answering numerous questions and creating an open environment to discuss this topic. Most importantly, I would like to recognize SSgt Ryan McBride for being the force behind the 3D printing and transforming the idea into a reality when it comes to aircraft usage.

I would also like to thank Capt Montana Ewers and Lt Brandon McClendon from the 86th MXG for their work in helping me identify the C-130J aircraft part to produce in concert with the 552d MXG. Your enthusiasm is greatly appreciated.

A huge thanks to Ms. Pamela Bennetbardot for your continued efforts to support the classes' research efforts and always doing so with a smile. I would like to express sincere gratitude to my sponsor, Mr. Donald Anderson for this topic and giving me an opportunity to tackle a subject that is important to me. Finally, to my advisor, Lt Col Joseph Huscroft for allowing me to run with the idea.

Major Michael J. Thompson

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I. Introduction

Background

> *"Nine times out of ten an army has been destroyed because its supply lines have been severed."*
>
> *Gen. Douglas MacArthur, General of the Army*
> *Remarks to the Joints Chiefs of Staff, 1950*

The Air Force fields a varied aircraft fleet ranging from advanced airframes such as the C-130J, C-17 and the F-22 to decades old workhorses such as the B-52G, KC-135R and the A-10. This large USAF aircraft inventory requires a robust manufacturing and supply chain to procure, transport, and overhaul millions of individual parts and material to maintain serviceability of the aircraft fleet. The USAF manages the material through Integrated Life Cycle Management (ILCM). ILCM is the seamless governance with transparent processes that integrate all aspects of infrastructure, resource management, and business systems necessary for successful development, acquisition, fielding, sustainment, decommission, and disposal of systems, subsystems, end items, and services to satisfy validated warfighter capability needs (AFI 20-101, 2013). The lack of responsiveness and agility in resource management and the supply chain can, at times, impact aircraft availability due to a lack of parts to the end-user. Focusing on one aspect to combat this lack of responsiveness, the Air Force can embrace new technologies to rapidly provide parts to the aircraft maintenance community and invigorant the supply chain. A solution to bridge this lack of responsiveness within the supply chain presents itself with the next advancement in manufacturing. The rapid evolution of additive manufacturing (AM), or more commonly termed 3D printing, can prove a viable supply option and manufacturing source for some aircraft part shortages and limitations (GAO, 2015).

The Department of Defense's (DOD) Logistics Enterprise and the Air Force ILCM encompasses contractors, sub-contractors and DOD entities to ensure parts are available worldwide for Air Force aircraft maintenance units to support their missions (AFI 21-103, 2013). This infrastructure is expensive, vast, and at times, incapable of supplying parts to keep the aircraft airworthy. This problem was addressed in the Air Force Future Operations Concept (AFFOC), *A View of the Air Force in 2035*.

> The timely and precise delivery of parts will be vital in the fights of the future. An acquisition and logistics enterprise that is capable of rapidly identifying, acquiring, and fielding solutions through organic additive manufacturing or commercial off-the-shelf sources (AFFOC, 2015).

This aforementioned vision is one of the 18 key implications outlined in the AFFOC's Strategic Master Plan with stated goals and objectives. In conjunction, the AFFOC's goal is to "develop an "agile acquisition" mindset that challenges bureaucratic inertia, streamlines processes, implements continuous improvement, and reduces risk through prototyping and new engineering development models" (AFFOC, 2015). Key to this Air Force vision of future capability is AM. To continue, "the vision for the logistics infrastructure will support a tailored forward presence from small, resilient bases, using dispersal, warning, active and passive defenses, rapid repair capabilities, and streamlined logistics through the use of additive manufacturing" (AFFOC, 2015). AM is not an Air Force initiative, AM is the technology of the future for all of DOD logistics and recognized in future planning and strategy, yet has an application today. The current Air Force aircraft maintenance community has yet to leverage or field AM technology to begin this transformation.

Viewing the current logistics structure and projecting the future logistics complex, it is certain the network includes manufacturing hubs, strategically-based warehouses and supply nodes, agile multi-model transportation capacity and personnel expertise to rapidly procure and move parts. The optimum supply situation for aircraft maintenance units now and in the future, is to have unfiltered access to all available resources and parts on-hand to repair and maintain aircraft instantaneously no matter the malfunction. Yet, it is currently impractical to field all the parts due to cost, weight, infrastructure, sheer numbers and parts availability across the globe; however, AM technology can begin to erode this tyranny of availability, time and distance when it comes to aircraft parts. The meteoric rise in AM technology has the potential to fill the void and field a capability for parts manufacturing and tooling at the tactical Maintenance Group (MXG) level which can optimize the innovative nature of maintenance personnel and begin to transform the current supply chain.

Most MXGs and aircraft maintenance units have select spare parts and a limited capability to manufacture and repair various items (AFI 21-101, 2015). For instance, structural and metals technicians are capable of structural repair, inspection, damage evaluation, inspects, repairs, manufactures, fabricates or modify metallic, composite, fiberglass, plastic components and related hardware associated with aircraft and special equipment (AFI 21-101, 2015). The focus of their manufacturing or fabricating effort is normally panels, brackets, cosmetic pieces, and at times major structural repairs and tooling for aircraft. For deployed units there are additional obstacles. Most deployed units field a limited backshop capability of skilled craftsmen such as the aforementioned metals technology and sheet metal technicians. These technicians are limited to manufacture aircraft parts by handheld methods using lathes, metal benders, and hand tools by forging parts which are not procurable within the supply system or currently unavailable. Access to raw materials, tooling and drawings (or samples) are used to transform ordinary stock metals, phenolic, fiberglass and various plastics into aircraft parts. Yet, the capability is limited by scope and capability of the supply chain. Aircraft maintenance units cannot bring all the raw materials forward in the case of deployed aircraft, nor can they outfit their deployed backshops with all the advance tooling such as waterjets, computer numerical controlled (CNC) machines or industrial machinery as the logistics footprint is normally too large. Parts not identified or authorized for manufacture within technical orders at the MXG level also limit the capability of maintenance personnel both deployed and at homestation (T.O. 00-25-195, 2012). Ordering the part through the supply system becomes the only option for many units which takes both time and money to procure and ship parts to the required location. AM has potential to provide a cost effective and agile capability both in a deployed location and at homestation for select parts. As the advance of AM continues to challenge traditional manufacturing methodologies, the Air Force must evaluate the benefits and cost of fielding 3D printers within their MXGs.

Air Mobility Command (AMC) has a unique set of logistical circumstances as aircraft flow through, in and out of a network of support bases and airports across the globe. In this role, AMC prepares and employs its forces to fulfill United States Transportation Command's (USTRANSCOM) global commitments to the Combatant Commanders (CCDR) and civilian authorities for airlift, aerial refueling, aeromedical evacuation, and Global Air Mobility Support System (GAMSS) support the CCDRs (AMCI 10-403, 2014). GAMSS are fielded with maintenance capabilities which are normally more robust than deployed locations and are akin to the main operating bases. There are limits to the aircraft maintenance capability as well. It can be difficult to rapidly procure parts to sustain the aircraft within this enroute structure. Many aircraft moving through GAMSS are time constrained and cannot wait for long expected-time-in-commission (ETICs) rates or parts procurement. When parts procurement do not meet mission timing (ETICs or mission requirements) decisions are made to either fly-as-is, cannibalize parts, switch airframes or perform temporary fixes to meet the mission (AFI 21-101, 2015). The use of 3D printers can provide another choice or capability to produce a point-of-use part for quick aircraft turn times or possibly temporary fixes to move aircraft through the system.

Leveraging innovation is important within the USAF. "Excellence in All We Do" drives us to develop a sustained passion for the continuous improvement and innovation that propels the Air Force into a long-term, upward vector of accomplishment and performance (AFI 1-1, 2014). The seeking of "excellence", powers innovation and has propelled technological advancement. Fueled by innovative thinking, Airmen have eclipsed technological barriers time and again. Arguably, the next opportunity to evolve our technology presents itself in the way we manufacture and produce goods. AM potentially provides rapid products across a spectrum of design and materials at a fraction of time and cost.

The types of products produced by 3D printing transcend society, from fashion accessories to heart valves to aircraft parts, these products are made with various forms of materials to supply businesses, consumers, entrepreneurs and innovators with an alternate method to manufacture goods which might be difficult to procure, complex to traditionally manufacture or easier with the newer technology (Barnatt, 2013) . The USAF aircraft maintenance community has yet to capitalize on the emerging AM capability for aircraft parts manufacturing, tooling and procurement. However, there are enclaves across the USAF where AM is moving forward as the research will demonstrate. This AM capability could enable aircraft maintenance units to produce small batch and samples off-setting procurement and transportation costs while making these parts readily available (save time and increase aircraft availability) at the wing level.

It is an optimum time to address AM for Air Force use, as it is rapidly emerging in the civilian and corporate sectors, as well as interest in various levels of the DOD and government organizations. Finally, applicability of AM can impact all facets of the Air Force as this AM proposal is valid across all competencies as the DOD continues to struggle through difficulty in procuring decades-old parts and impending fiscal constraints.

Problem Statement

The rapidly evolving AM (3D printing) capability presents an alternative supply stream for sourcing of aircraft maintenance parts. Original Equipment Manufacturers (OEMs) are leveraging 3D printed parts, manufacturing various items to include aircraft parts. The Air Force will eventually field 3D printers to produce an assortment of products which includes aircraft part prototyping, limited manufacturing and tooling (AFFOC, 2015). Yet the Air Force aircraft maintenance community has not invested in 3D printer suites at the MXG level to begin the process of familiarity and acceptance of this new technology. An opportunity exists to leverage 3D printers and the innovative nature of field-level aircraft maintenance personnel to find opportunities to apply this technology to assist in minimizing cost, streamlining parts procurement, prototyping parts, secondary parts manufacturing and alternative tooling.

Research Questions and Hypotheses

The hypothesis of this research project is MXGs stand to gain parts availability and flexibility by leveraging current AM and 3D printing capability for aircraft maintenance. The research is designed to ascertain if fielding 3D printers at their current technological state can be used within AMC at the MXG level. To determine whether or not AMC will see an adequate return on this investment, the research project seeks to answer the following questions:

1. Is AM technology mature enough to warrant adoption at the MXG level to produce viable aircraft components?
2. If so, can a proof of concept be made to print an aircraft part?

After research and analysis, additional and secondary questions were posed to build a case study and proof of concept. These questions further defined the nature of the research and are as follows:

3. What 3D printer capability that exists which can produce viable aircraft parts?
4. If so, what types of material and aircraft parts can be printed for aircraft use?
5. Can this 3D capability be replicated and used among other MXGs?
6. What part(s), if any, can be printed and can it be replicated on another airframe?
7. What is the value to the unit to print the part? What savings occur (if any) in time, money, manpower and resources?

Research Objective and Focus

The Air Force aircraft maintenance community has not measured the ability of MXGs to field 3D printers to supplement current wing-level fabrication, manufacturing and parts development. This research focused on a case study of the 552d MXG's use of a 3D printer and the innovative products being developed. It delved into the value in both time and money saved, while highlighting the manpower savings, avoidance of hazardous materials, producing unavailable non-mission critical parts with a certified thermoplastic media (ULTEM 9085) and supplemental tooling for traditional manufacturing techniques. Furthermore, the research presented a proof of concept by selecting a C-130J Aft Cargo Door Rub Strip to manufacture and produce the prototype part. The Literature Review provided an overview of AM techniques and products which will be used as a backdrop of information to power the analysis of the case study and proof of concept. Ultimately, though this research, this paper seeks to provide a baseline of data to determine if fielding 3D printers at the MXG level is appropriate.

Methodology

This research canvassed the DOD, governmental organizations and the civilian sector for AM initiatives. The initial focus was to find the most advanced AM process, rooted in an aircraft grade metal and materials, for the case study and the proof of concept. After analysis of current technologies, visits to both Defense Advanced Research Projects Agency (DARPA) and Naval Air Systems Command (NAVAIR) AM processes, it was determined metal 3D printing has not matured enough for implementation at the MXG level at the time of this study. Difficulties in metallurgical consistency, inspections processes, hazardous waste and metal powder cost are some of the mitigating factors. However, the research question posed did not specify material, rather, it asked if 3D printers can produce any aircraft part. The focus of research moved to the more accepted use of plastics for use as nonstructural, secondary parts on aircraft, which met the intent of the paper.

Furthermore, to determine if a viable plastics AM process existed for aircraft, the research shifted to aircraft maintenance units across the Air Force. The 552d MXG presented itself through an article highlighting the use of a locally procured 3D printer using a thermoplastic to make a seat endcap for the E-3 Airborne Warning and Control System (AWAC) (Parker, 2015). A site visit and case study determined if the technology met the research paper's criteria and if the process to was transportable to other MXGs and airframes. The research delved into the reasons the 552d MXG's implemented the 3D printer and the how the application of the technology grew.

Finally, addressing the final aspect of this research project, a proof of concept, required the selection of another MXG and an airframe to produce a prototype part. Selection of the C-130J was critical as it encapsulated the lessons from the case study and the airframe part is common to both the legacy platforms and modern C-130 airframe. The C-130J is interesting as it has many similar parts which transcend the older C-130 airframes, which reinforces the paper's impact of producing 3D printed parts for both legacy and modern airframes. The final selected part for manufacture was a C-130J Aft Cargo Door Rub Strip as a viable candidate for 3D printing and the proof of concept. In conjunction with the 552d MXG 3D printer, the part was manufactured to physical specifications using aircraft drawings.

Assumptions/Limitations

This research maintains a number of simplifying assumptions. First, it assumed there is an appetite to acquire AM in the Air Force's aircraft maintenance community. Secondly, as the research quickly demonstrated metal parts appeared to be beyond the scope of this research, the focus of the 3D print technology honed in on plastics foregoing detailed research into metal implementation. This also drove investigation into secondary structure and non-mission critical parts, avoiding analysis of primary structures as well as a focus on plastics and phenolic.   It is also imperative to recognize 3D printing is a supplemental manufacturing technique, not a mass producing manufacturing process. It is assumed the Air Force is interested in 3D printing to supplement the current supply chain and the use of prototyping.

One key limitation is the enormity of information available and the speed of change within the AM community which can stifle research progress. Additionally, the scope of ownership of technical data is beyond this research. This paper will not address the legal implications of 3D printing nor the licensing process requirements. Specifically, the research into the intellectual property (IP) issues and ownership of IP will not be addressed. Furthermore, the proof of principle produced a part, but had not completed the process to certify its use on an aircraft. Finally, the research uncovered various applications within the DOD and Air Force; however this paper does not address the implementation or application of AM beyond the aircraft maintenance community.

Implications

The implications of adopting AM methodology and 3D printers can not only impact aircraft maintenance, it has the potential to fundamentally shift the DOD supply chain and logistic network. Specifically, within the application of AM in the aircraft maintenance community, the ability to field a 3D printer to produce aircraft parts can increase aircraft availability, lower costs and provide point-of-use logistics at the tactical level. Aircraft turn times for repairs can rapidly decreased as unit can avert the delays for parts transiting the supply system. AM would augment current manufacturing at the wing level using traditional manufacturing processes such as CNC machining, lathes and waterjet operations.

Prototyping becomes an option for aircraft technicians. The ability to print exact copies through scanning and additive processing techniques can build cheap prototypes which can be transferred to more expensive metals to manufacture through traditional methods. Recapitalization time and material cost versus traditional processing is also possible. The implications listed will fail to encompass what the positive impact and ideas generated by adding 3D printers to the aircraft maintenance units to rapidly manufacture parts for aircraft.

II. Literature Review

Chapter Overview

A recent literature review identified thousands of article, papers, books and webpages about AM and 3D printing. The expanse of data and expert opinions are overcome by the sheer number of individuals seeking information on how to 3D print. A search for information found AM in many disciplines from aerospace, medical, food and transportation to name a few. The following pages will delve into what 3D printing entails and overview popular methodologies with a deeper understanding of Fused Deposited Modeling as the research focused on that technique. The section continues by exploring some of the various industries utilizing 3D printers and the use within aerospace and the different initiatives within DOD.

Additive Manufacturing

Background

The Air Force shall promote the development, protection, and integration of technology throughout the life cycle that advances state of the art warfighter capabilities critical to continued superiority in air, space, and cyberspace (AFPD 20-1, 2012). The continued efforts to revolutionize technology transcend the Air Force culture. AM's emergence as a viable manufacturing method must be measured within the aircraft maintenance community. However, embracing this change can be difficult as it can be within the private manufacturing community. Lessons from industry can assist the Air Force's transition with AM. Experts within aviation point out the safety conscious nature of aerospace, this mentality is necessary; however, this does pose an obstacle for AM application. Barnatt cites the educational aspect of AM is vital in seeking acceptance. AM's education is of key importance because unfamiliarity with AM technologies is one of the barriers to its widespread adoption (Barnatt, 2013). It is the intent of the research to provide some clarity to AM.

AM is a subset of Direct Digital Manufacturing. It encompasses automated machines manufacturing parts from computer-based drawings known as Computer-Aided Design (CAD) or Computer-Aided Manufacturing (Tadjdeh, 2014). It differs from traditional manufacturing techniques whereas the material is additive in nature versus subtractive (Figure 1). The traditional method of manufacturing is also referred to as subtractive manufacturing where a machine such as a lathe or mill removes the material to produce the final product (GAO, 2015). In comparison, AM produces considerable savings in waste material as opposed to subtractive manufacturing, therefore there is a cost savings associated in material using AM.

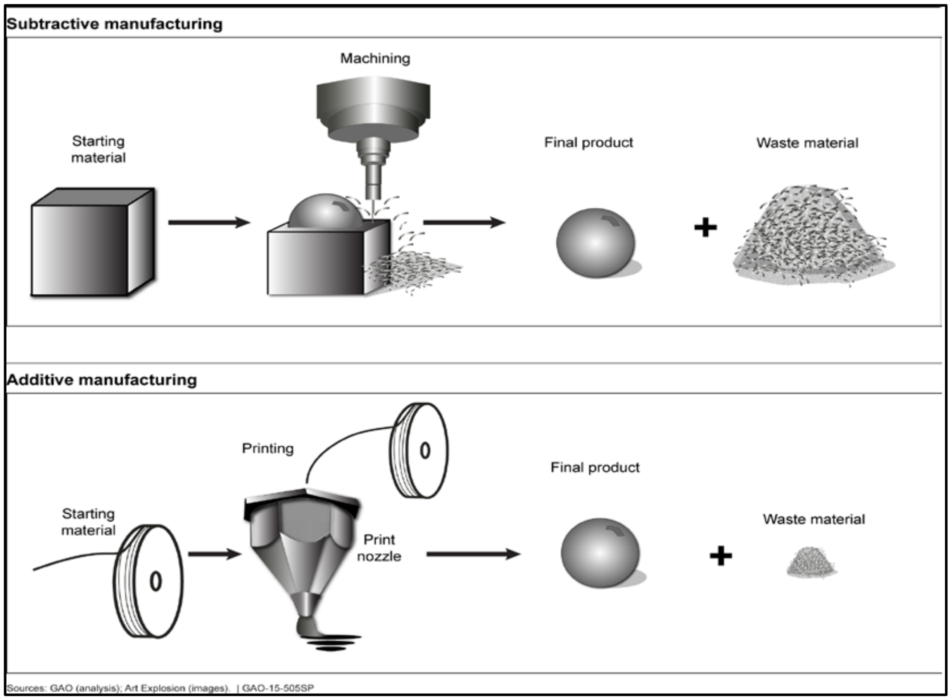

Figure 1. Representation of Subtractive and Additive Manufacturing (GAO, 2015)

The ability to utilize a different method to manufacture and fabricate complex geometric shapes, not capable through traditional manufacturing, can fundamentally shift the way to manufacture parts within industry (Barnatt, 2013). How AM works is fairly simple. It is the layer-by-layer fabrication of parts using a solid, liquid, semi-liquid or powder substance (Kurman, 2013). The substances can range in composition from metal, polymers, plastics and even food substances. The benefits of this processing technique is the lack of constraints which are present in traditional manufacturing processes such as forging or milling. The geometric constraints imposed by traditional manufacturing processes are overcome by building the part from the inside out or bottom up.

The common method to produce the "picture" or "blueprint" within CAD is through the .stl file. The .stl file was created in 1987 by 3D Systems Inc. when they first developed stereolithography, and the .stl file stands for this term or also known as

Standard Tessellation Language (Hernandez, 2012). To make the part, the CAD programming converts the drawing, schematic or scanned part into a .stl file. The process models within the CAD software, translates to a .stl file which the pieces are "cut in slices" containing the information for each layer (Hernandez, 2012). Through a series of steps, the .stl is created by converting continuous geometry in the CAD file into a header, small triangles, or coordinates triplet list of x, y, and z coordinates and the normal vector to the triangles (Hernandez, 2012). The resulting steps create boundaries and references axis, with the final product resulting in a computer file akin to a picture which a 3D printer can interpret. The result is a part or object to the specifications of the drawing. Melding the design criteria, the employment of CNC machines function with the same .stl formatting, easily transferring designs from CNC machines to 3D printers.

The multiple processes outline (Figure 2) broadly represent the AM community and methodologies. The list includes many different methods such as fused deposition modeling (FDM), stereolithographic (SL), Polyjet, laminated object manufacturing (LOM), selective laser sintering (SLS), electron beam melting (EBM), laminated engineered net shaping (LENS), 3D printing (3DP), and Prometal. The research paper focused on FDM modeling of a thermoplastic; however, a brief overview of each method is warranted.

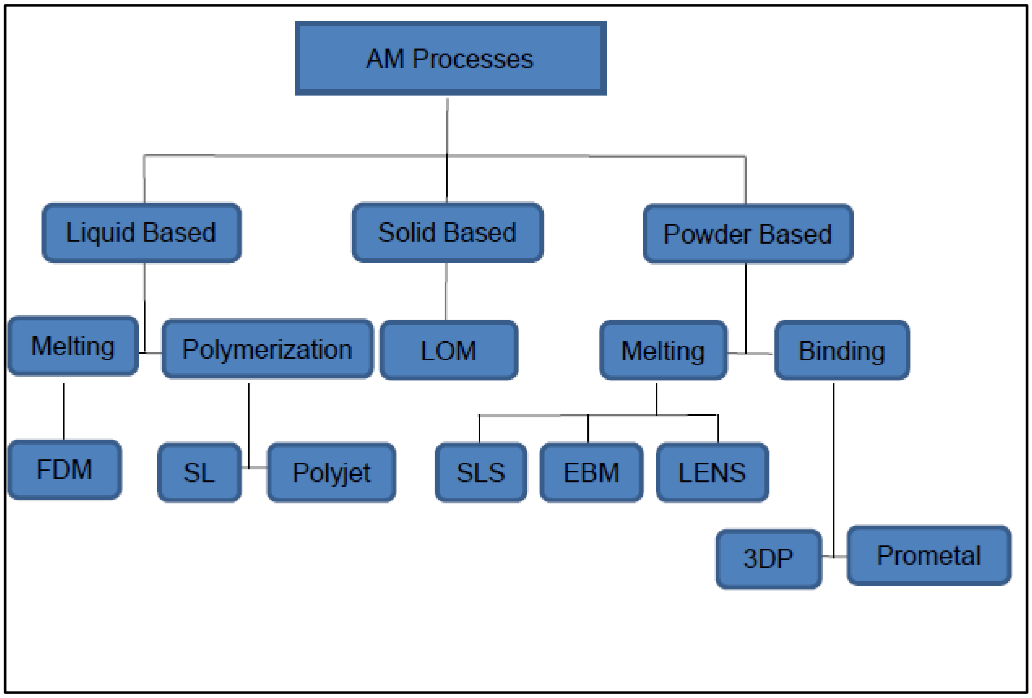

Figure 2. Additive Manufacturing Methods, (Hernandez, 2012)

Stereolithography

SL is a liquid-based process that consists in the curing or solidification of a photosensitive polymer when an ultraviolet laser makes contact with the resin also known as polymerization (Hernandez, 2012). This type of plastic simply hardens to create the parts dictated by the computer. To create the parts, a manufacturing build platform is perforated and sits just beneath the surface of a vat of liquid (Figure 3). An ultraviolet laser traces the outline of a part on the liquid surface from the .stl file, which causes the photopolymer liquid to "cure" on the build platform (Barnatt, 2013). The build platform moves down, by a fraction of a millimeter, as each layer is cured. Liquid flows over the top creating another layer to be cured.

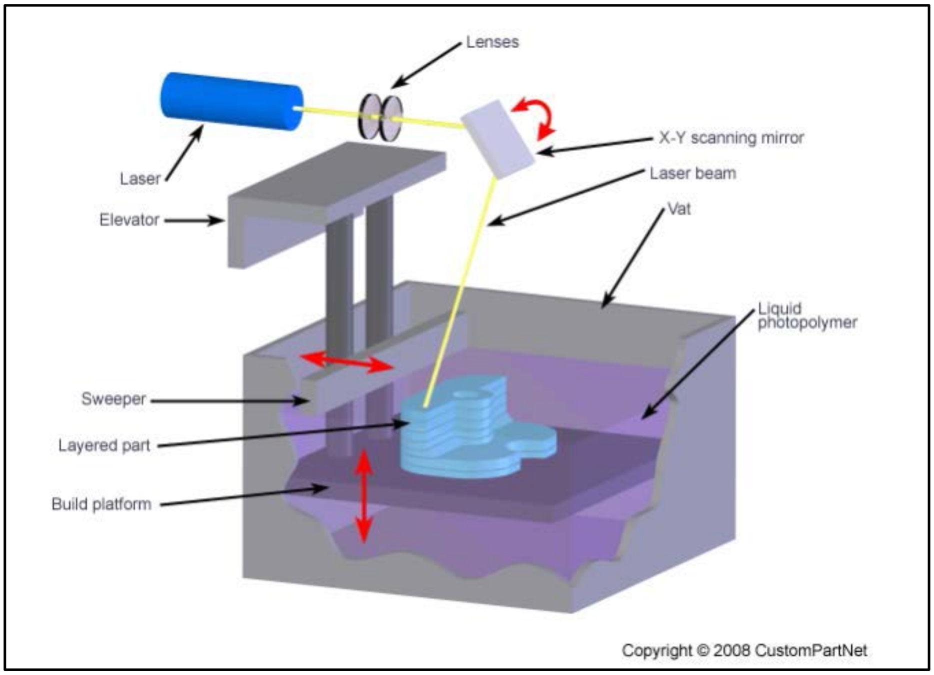

Figure 3. Stereolithographic Processing (CustomPartNet, 2008)

Fused Deposition Modeling

The advent of thermoplastic extrusion has propelled this category into the most common form of 3D printing today (Barnatt, 2013). FDM became the focus of the research as this methodology was central to the case study. Within thermoplastic extrusion exists the method known as FDM. This method consists of extruding a semi-liquid material or multiple semi-liquid materials from a computer controlled printer head (Kurman, 2013). FDM utilizes a filament of plastic, housed in casings or rolls, then fed through the print head nozzle where the material is heated to a semi-liquid or liquid state. For reference, picture the concept similar to a glue gun for home use. The printer head translates the .stl file, by depositing the shapes outline akin to tracing an outline on a piece of paper. After the part is “traced”, the printer head deposits the remaining material within the outline. Successive layers of the material are added to produce the part (Figure 4).

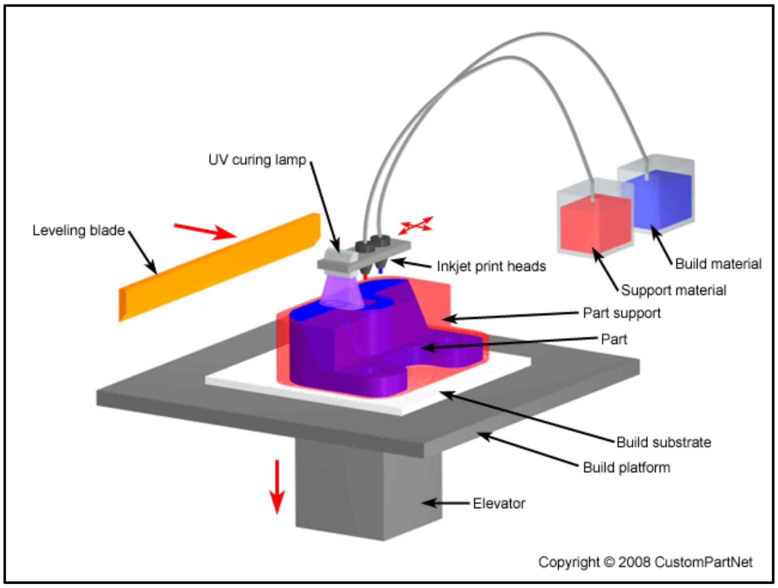

Figure 4. Fused Deposition Modeling, (CustomPartNet, 2008)

A leader in the FDM community, Stratasys produces advanced and industrial FDM 3D printers (Stratasys, n.d.). The case study analyzed the employment by the 552d MXS to use one FDM printer (Model #400MC) and the certified thermoplastic material ULTEM 9085. The Stratasys 400 MC is an FDM 3D printer utilizing 230 VAC, 50/60 Hz, 3 phase, 16A power requirements (Stratasys, n.d.). The unit is capable of printing on a build platform producing parts as large as 14.97 x 10 x 10 inches (355 x 254 x 254 mm). The limits of size can be overcome with building seams on parts to create larger projects. FDM Technology works with production-grade thermoplastics to build tough, durable parts that are accurate, repeatable and stable over time. The capability di to 3D print your concept models, prototypes, tools and production parts in familiar materials like ABS, PC and high-performance ULTEM 1010 and ULTEM 9085 (Stratysys, 2015).

As an OEM, the onus to produce a material certifiable for aircraft use fell on the company (Figure 5). An analysis of the materials central to this study deals with the use of ULTEM 9085 Thermoplastic. According to Stratasys, ULTEM 9085 has a reputation for reliability, a famously overachieving thermoplastic has well-rounded thermal, mechanical and chemical properties that make it superior in most categories (Stratasys, n.d.). To seek authorization for use, Stratasys had to test the material to prove the claim. These tests for certification are rooted in engineering reliability and present the probability that an item will perform a required function without fail under stated conditions for a stated period of time (O'Connor and Kleyner, 2012). The tests included strength, temperature, heat, tensile and shear. Further research uncovered the litany of certifications ULTEM 9085 received throughout testing. The standards met are far reaching and include standards in American Society for Testing Material (ASTM), UL94 Standard for Tests for Flammability of Plastic Materials, Federal Acquisition Regulations (FAR), joint statutory authorization (from DOD, GSA and NASA), and MIL-STDs (ANSI, 2002). Additionally, testing included the CFR§ 25.853 for Compartment interiors. This testing certifies materials used in crew and passenger aircraft usage (ANSI, 2002).

As stated in the AFFOC, *Vision of 2035*, the use of this 3D printer met the intent of COT capabilities which the Air Force should seek to employ. To gain acceptance of ULTEM 9085 as a viable material to produce aircraft grade parts, Stratasys sought Federal Aviation Administration (FAA) approval for the material. Paralleling the FAA use, recently, ULTEM 9085 was approved for us on an Air Force E-3 AWACs as the material for a replacement part to passenger seat covers (Parker, 2016).

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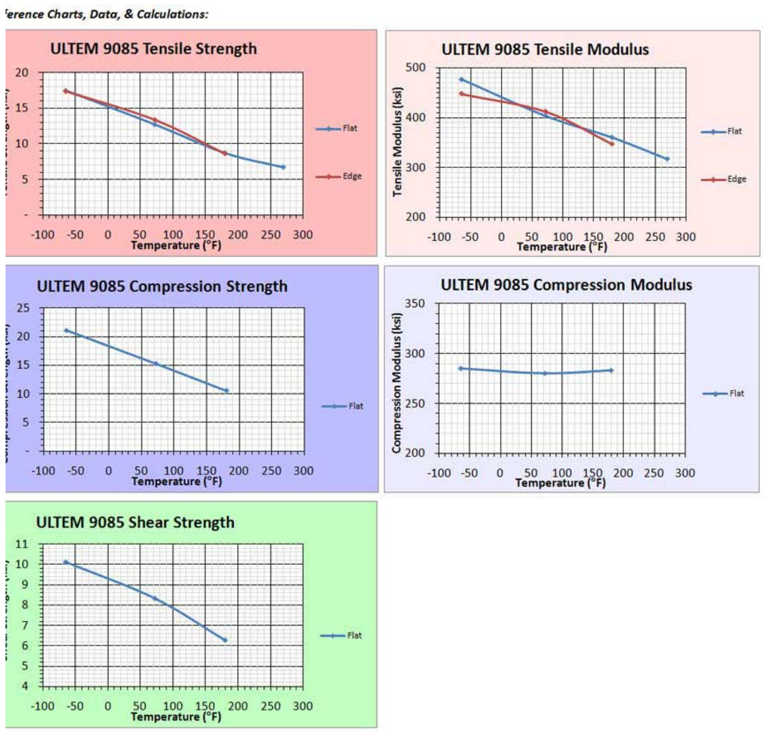


Figure 5. ULTEM 9085 Test Results

Polyjet

Polyjet is a relative newcomer to 3D print technology utilizing methods from other related 3D printing processes (Barnatt, 2013). The Polyjet printer has a printer head which sprays liquid photopolymer into extremely thin layers and firms up the layers by using an ultraviolet light (Figure 6). This method bodes a tremendous advantage as the spraying of the material can be as thin as 16 microns (Kurman, 2013). The material is weaker than other methods such as SL. The method resembles traditional inkjet printing which allows this printing methodology to print in multiple colors.

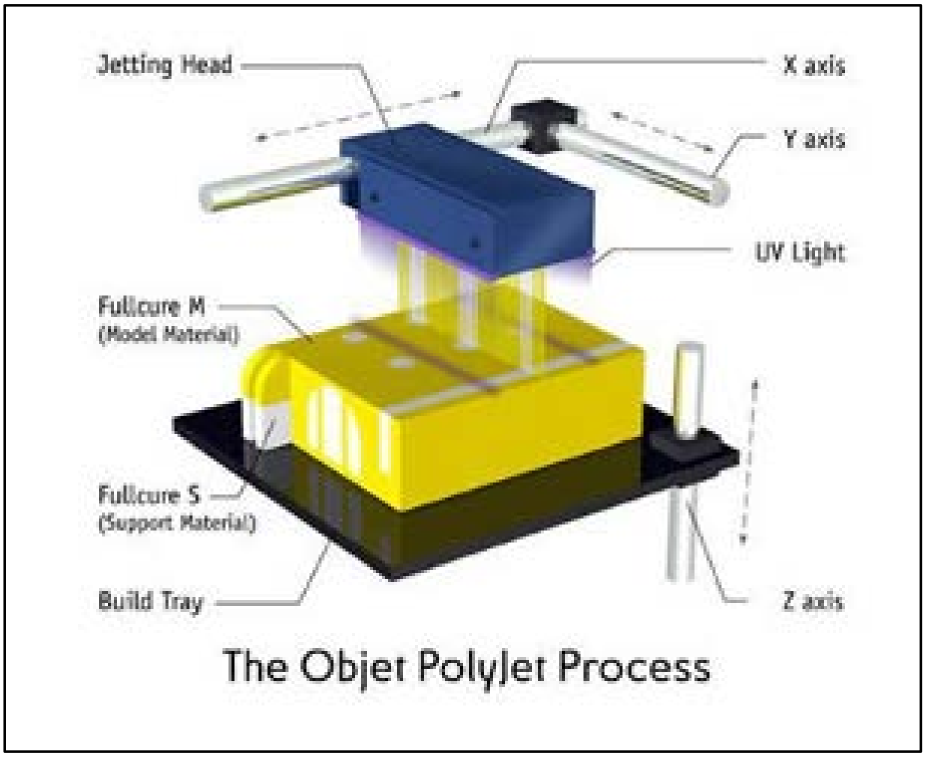


Figure 6. Polyjet Printing Method, (CustomPartNet, 2008)

Laminated Object Manufacturing

LOM builds objects in layers by sticking together laser-cut sheets like paper, plastic and metal foil (Barnatt, 2013). This method is unique in that it adds both the traditional subtractive methodology with techniques from AM. The combination of the two methods is an interesting use of AM. Within the research, the case study highlights how partnering subtractive and additive is beneficial.

The material used in this process traditionally comes in sheet form and bonded together (pressure and heat) in conjunction with a thermal adhesive coating

(Hernandez, 2012). A laser is used to cut the material after each successive layer is deposited on the build platform (Figure 7).

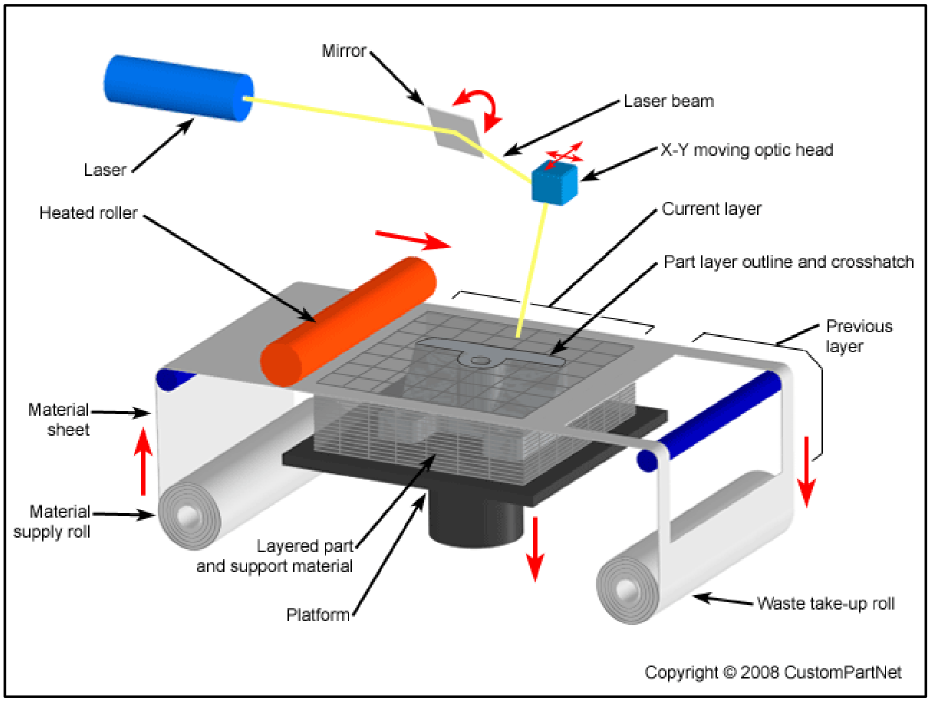


Figure 7. Laminated Object Manufacturing, (CustomPartNet, 2008)

Selective Laser Sintering

SLS also known as direct metal laser sintering highlights the versatility powder materials within AM to make parts. The original focus of the research originally delved into this process as this is a preferred method for most metal parts manufacturing. This process uses a powder (various plastics, metals and polymers) which is sintered or fused by the application of a laser. The machine is heated internally; the chamber is almost the temperature of the material making filled with an inert gas (Hernandez, 2012). The laser moves across the build plate, fusing the powdered material. The build plate is covered by a small layer of material that is laid out as a film on the plate

(Figure 8). As the laser passes over the material and finishes the sintering, another layer of material is deposited and the build plate drops. Only metal particulars touched by the laser will fuse.

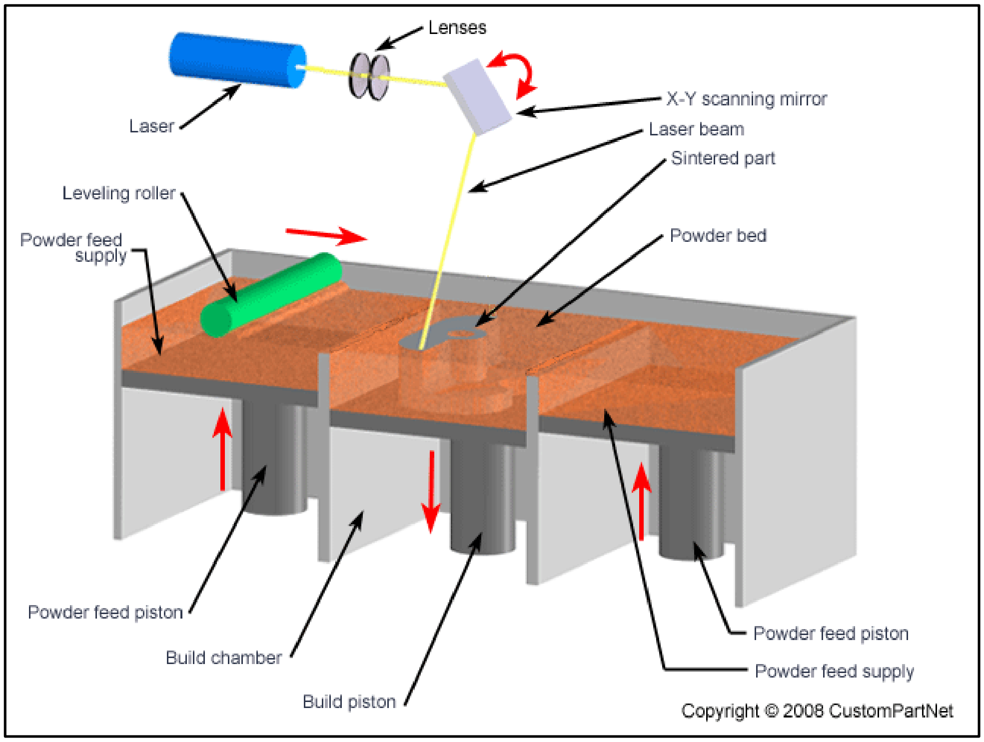


Figure 8. Selective Laser Sintering, (CustomPartNet, 2008)

NAVAIR operations at JBMDL, New Jersey uses a SLS machine for their prototyping of naval aircraft parts (Merk, 2015). Their AM work focuses on the use of primary structures and aircraft titanium. Merk explained they are building parts and test coupons on build plates out of titanium. The intent is to provide the reliability and engineering data with all the AM builds to provide a database. Reliability testing is integral to all manufacturing methods (Kleyner, 2012). AM methods are expected to meet the same rigorous testing and quality standards.

Electron Beam Melting

A similar process to SLS is EBMA. The methodology of placing the material and how the process works is the same as SLS. The differences begin with the use of an electron laser beam powered by a high voltage, typically 30 to 60 KV, to sinter or fuse the material (Hernandez, 2012). The chamber is also different whereas a vacuum is used to remove oxygen to avoid oxidation. This process is designed to make metal parts as well (Figure 9).

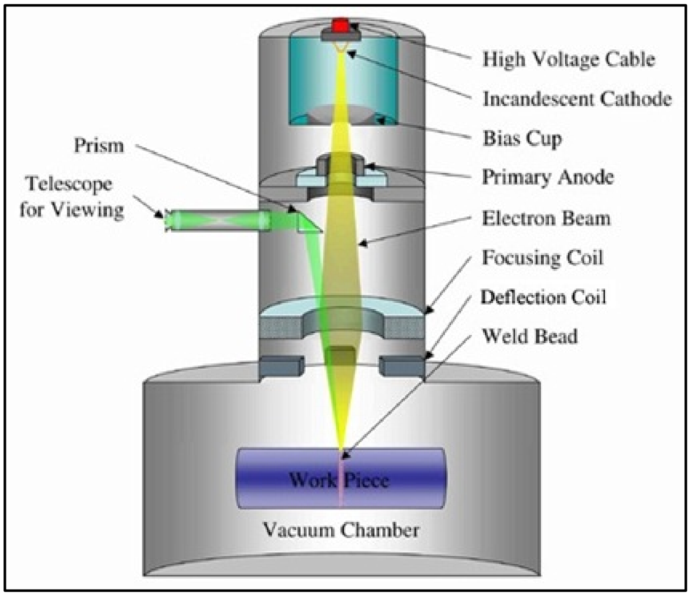


Figure 9. Electron Beam Melting, (CustomPartNet, 2008)

Laminated Engineered Net Shaping

LENS builds a part by melting a metal powder, then injects the molten material into a form. Again, this method uses a laser similar to SLS or EBMA to melt the material and once injected, the material cools. This process uses a chamber with argon gas and is capable of producing parts made stainless steel, titanium and aluminum (Hernandez, 2012).

Three Dimensional Printing

To confuse the AM world, 3DP is a well-known process. It is a MIT-licensed process in which water-based liquid binder is supplied in a jet onto a starch-based powder to print the data from a CAD drawing (Kurman, 2013). The powder particles lie in a powder bed and they are glued together when the binder is jetted (Hernandez, 2012). The reason the process is called 3DP is the resemblance to inkjet printers used for traditional printing.

PROMETAL

Prometal is a process which uses a liquid binder shot in jets onto steel powder. The build plate holds the powder in place and moves down as each layer is created. After finishing, the residual powder must be removed. When building a mold, no post-processing is required. If a functional part is being built, sintering, infiltration, and finishing processes are required (Hernandez, 2012).

Additive Manufacturing Within Industry

> *"The 3D printing market grows at a compound annual rate of 23 percent from 2013 to 2020, reaching $8.4 billion."*
>
> *Marketsandmarkets.com, 2016*

Developments in AM have been cited as the second industrial revolution (Bianchi, 2014). As 3D printers continue to fall in price, and growing familiarity feeds an increased appetite for this technology. It is argued, AM can make the production of goods cheaper at times, widely available and customizable. It is this argument expert cite this technological revolution will touch all industries within the civilian sector. Already evident from the medical community to aerospace, 3D printers are producing products for industry and the everyday user (Brooks, 2006). Although analysts still consider the AM market to be a niche sector, they nonetheless state that it had a volume of up to €2 billion ($2.44 billion) in 2012 (Siemans, n.d.). "The rapid growth in AM is projected to increase by 300% by 2020" according to Wohler's Report 2015 (Millsaps, 2016). This market will provide better access for 3D printing for many industries and individuals.

Table 1. Leading industrial AM vendors, 1988 -2011 (Wohlers, 2012)

Vendors/Production Sites	**Processes/Applications**	**Materials**
3D Systemsa (US, AUS, NED, ITA)	Binder jetting, material jetting, vat photo polymerization, powder bed fusion	Plastic, polymer, metal
Beijing Tiertime (CH)	Material extrusion	Polymer
DWS (ITA)	Vat photo polymerization	Polymer
Envisiontec (GER, US)	Vat photo polymerization , material extrusion	Biomaterial, ceramic, polymer
EOS (GER)	Powder bed fusion	Ceramic, metal, polymer
ExOnea (US, GER, JPN)	Binder jetting	Ceramic, polymer, metal
Objetb (ISR, US, GER, Asia)	Material jetting	Biomaterial, polymer
Solidscape (US)	Material jetting	Plastic
Stratasys[a, b] (US, GER, IND)	Material extrusion	Polymer
Z Corp. (US)	Powder bed fusion	Plastic, metal

In the history of manufacturing, AM is a relatively new technology which was news worthy over the past ten years or so, the widespread use of additive manufacturing within the aircraft industry and has been around for the past 30 years (Zelinski, 2015). Leading the airline industry is General Electric (GE, 2015). On the forefront of AM technology, GE is regarded as the largest manufacturer of AM within the world (LaMonica, 2015). According to the GE's newsletter, GE sought to recently reinvest in new advances in this technology and bored out two smaller companies to develop future application in 2015 (Americanmachinist, 2016). Expanding their use in aerospace, GE engineers are exploring using AM for more aircraft parts to include engines (GE, 2015). Leveraging newer materials such as alloys, titanium, and aluminum can lead to further uses throughout GE. GE has been a pioneer in the application AM, in particular within the GE Aviation business, which has adopted AM to produce fuel nozzles and other engine parts (GE, 2015). GE has produced parts for aircraft engine use made of advanced materials (Kenney, 2013) which flew after FAA certification (Kellner, 2015). Not to be outpaced, Lockheed Martin (LM) also incorporates AM within their manufacturing. LM believes AM will play a major role in their aircraft production (Zelinski, 2015) in the future. The third member of the large domestic aircraft manufacturers is Boeing. They have invested in AM on a large scale and continue to forge ahead. In 2015, Boeing received Federal Aviation Agency (FAA) certification to use 3D printed parts for certain applications (Dickey, 2013). One motivation for the aerospace industry cites weight. AM can provide alternate methods to produce products at a lower weight. Removing one of weight out of an aircraft can save over $10,000 in fuel costs every year (Kenney, 2013). AM parts allow for structures to reduce the material by 75% focusing on the required structure. This is lightweight in design which subtractive manufacturing is limited by the geometry to remove material. Additionally, expensive materials such as titanium are traditionally milled with up to 90% waste stream versus virtually no waste stream for AM. AM is matriculating throughout aviation and finds itself utilized in other fields as well.

As the AM technology advances, it gains attention to other which feed the technological advancements. With the application of AM moves into various sectors such as medical and dental, we find a lucrative environment. From 3D printing cells and skin, to creating bones and prosthetics, AM is transcending the medical world and research. Within the cardio vascular practice, a new study from Texas A&M joining robotics and AM to personalize treatment. In the study, 3D printed, tailor-made stents and scaffolds could have a massive impact on the success rate of the (heart) surgery (Hall, 2016). With such tight tolerance, 3D printing can present perfect inserts meeting the patient's individual needs, customizing each surgery.

The dental community uses 3D printing for various dental works and prototyping. Using the same methods found in the aerospace industry, dentists can now rapidly scan and print dental pieces such as crowns, bridges, stone models and a range of orthodontic appliances. A recent article in Harvard Business review summaries the application of 3D printers within the dental specialty. "However, this time instead of a physical mold my dentist inserted a digital camera in my mouth and the next thing I knew a digital image of my damaged tooth immediately appeared on a computer screen positioned right next to my dental chair. I watched my damaged tooth rotating in all of its 3D glory when he ran the design software to quickly and magically fit a digital crown on top of my chipped digital tooth…in about ten minutes, with my new crown in hand, it was back to the dental chair where it was expertly put in place permanently" (Kaplan, 2014). This research demonstrates the point-of-use capability of 3D printing, to manufacture a customized part at the tactical level and roots itself in the earlier stat AFFOC, *A View of the Air Force in 2035*, "timely and precise delivery of parts" and "rapidly identifying, acquiring, and fielding solutions through organic additive manufacturing" (AFFOC, 2015).

Yet, AM still has a healthy following in the prototyping world. Over 278,000 desktop 3D printers under $5,000 were sold throughout the world in 2015 (Millsaps, 2016). Researchers from Johns Hopkins University Applied Physics Laboratory have developed a 3D printed prototype of an unmanned aerial vehicle (UAV) external tank. Tests carried out on the Corrosion Resistant Aerial Covert Unmanned Nautical System (CRANCUNS) have proven that it can remained submerged in saltwater for two months, and then be launched into the air to carry out its mission. CRACUNS enables new capabilities not possible with existing UAV platforms (Brown, 2016).

Additive Manufacturing Within DOD

From the military perspective, there are numerous articles and research papers regarding AM technology. Recent studies and implementation across the DOD has ushered in a period of experimentation and testing to advance 3D printing, For instance, the U.S. Navy leads efforts with a tremendous vigor. With fielding ships with a 3D printer (Merk, 2015) and producing an aircraft engine valve (Merk, 2015), the Navy is a prolific supporter of 3D printing. The cost estimates of introducing 3D printing and the subsequent collaborative product lifecycle management across the Navy shows positive results with a cost savings of $1.49 billion annually (Kenney, 2013).

From an Army perspective, research into the applicability to use in the field is on-going. By lifting the logistics burden and minimizing weight and cost facing the Army, soldiers can rationally expect 3D printers in the field in the future. Citing both U.S. government initiatives, there is an overriding effort to leverage this technology over the next ten years (Drushal, 2013). According to Dr. Thomas Russel, director of the U.S. Army Research laboratory, "One of our biggest challenges in the Army is that there is a huge logistics burden" (Russell, 2014). One interesting direction pursued by the Army is to consolidate the capability into a Center of Excellence (Drushal, 2013). The Army has taken the next step by fielding forward-deployed 3-D printing labs in Afghanistan known as the Rapid Equipping Force (REF), allowing units to optimize AM technology in the field.

The DOD sets the standards for the individual department's success with transforming technology into reality. Citing the advent of AM for future logistics, the Government Accounting Office (GAO) determined that the DOD May 2014 additive manufacturing briefing for the Senate Armed Services Committee addressed three directed elements: potential benefits and constraints, potential contributions to DOD mission and transition of the technologies of the National Additive Manufacturing Innovation Institute DOD use (GAO, 2015).

The DOD took steps to implement AM to improve performance and combat capability as evident by the initiatives of the subordinate services. The GAO study cites a need for the DOD to take steps to fully control and implement AM measurement and management. It is the belief, introducing oversight will assist in the sharing of AM technology between services and DOD agencies. The recommendation from the GAO is to synergize the AM community for cross tell and control by designating an Office of the Secretary of Defense lead to be responsible for developing and implementing an approach for systematically tracking department-wide activities and resources, and results of these activities; and for disseminating these results to facilitate adoption of the technology across the department (GAO, 2015).

A recent Delphi study advocates Air Force Civil engineers could use the capabilities of a 3D printer for use in CE operations. (Poulson, 2015) The study finds there will be a viable technology level by 2020 to use AM in deployed operations. This suggests there are pockets of initiatives across the Air Force to foster innovation and apply 3D printers within normal operations. However, there are sincere concerns the technology has not evolved enough for aircraft use. Addressing this technological gap is important. However, as noted in numerous reports the technological advancements will overcome this hurdle within the next few years (Epstein, 2015).

A 2015 Air Force Research Laboratories contract for $1M and the DOD's small business initiative worth $900K highlights the Air Force's view that AM is a viable component within the aerospace industry (Abaffy, 2015). A stated earlier, the Air Force broke a barrier in January 2016 by approving their first AM replacement part on an E-3 aircraft (Parker, 2016), which became the focus of the case study presented in this research. A generalized discussion with aircraft maintenance experts cited concerns and hesitation in the technological gap which could exist with the current technology. However, it is certain the technology will overcome this problem (estimated within the next 5 -10 years) (Kenney, 2013). The impetus for this research lay in the hesitation of aircraft maintainer's adoption of this AM technology.

The Air Force presented the opportunities to business, a strategic AM roadmap by Tom Naguy, HQ AFMC/A4U on 19 November 2014. It is important to cite within the presentation, the Air Force's view that "there is an immediate value in AM technology for tools, fixture, prototypes and non-critical parts." OEMs were given the criteria and the roadmap to work within the Air Force to garner opportunities to filed AM technology meeting specific criteria (Naguy, 2014). There is another argument to utilize COT AM technology form OEM and employed organically to meet Air Force needs. This is supported by strategic guidance such as the AFFOC, *A View of the Force 2035*.

Summary

This chapter highlights the abundance of AM methodology used to produce manufactured parts. Form liquids to powders, there are methods to manufacture goods via additive measures versus subtractive. As the technology evolves, the movement from industrial sectors which utilize AM expands, bringing the technology into other corners of the civilian market. OEMs within aerospace are motivated to adopt AM to cut costs and liberate the constraints set by traditional manufacturing techniques. The DOD understand and supports the use of AM throughout their agencies. All the services employ AM to some degree with research ongoing to identify new uses of the technology. The next chapter will explore how methodology used to gauge the use of AM in aircraft maintenance

III. Methodology

Chapter Overview

At the time of this research, the Air Force has one known fielded 3D printer in use at the MXG level producing aircraft parts and tooling. This research methodology first focused on the initial investigative question, which was to determine if to if there is a 3D printer capability that exists which can produce viable aircraft parts. A case study was the preferred method to evaluate this question and the overall effectiveness of this lone MXG 3D printer program. The second overall question, determining if the 3D printer capability can be used with by other aircraft maintenance units to print parts, was addressed using a proof of concept. A proof of concept was preferable to test if there were other viable parts, from other another organization to 3D print. The focus was to determine the feasibility of the aforementioned MXG's 3D print process application to another unit and their unique circumstances. Using both methodologies, the goal of the research is to garner an understanding of how AM can work within the aircraft maintenance community and if it is practical to invest in 3D printer suite for MXGs.

Case Study Methodology

Case studies are a research method aimed at holistically analyzing a phenomenon in its context (Yamashita and Moonan, 2014). The difficulty with case studies is each situation is different and it can be difficult when generalizing data, knowing the factors change when applying results to other situations. Yamashita and Moonan argue that case studies are a promising instrument to study the complex phenomena at play (Yamashita and Moonan, 2014), when dealing with complex issues. Case studies do become intricate when addressing multiple cases and ascertaining their impact. The goal of the case study is a complete evaluation of factors which allow readers to draw conclusions about the extent of the case. The reader can then relate the case study's findings to the applicability of other situations garnering insight into a related field.

An interesting point came from Leedy and Ormond, there is a difficulty with using one case study. It is their opinion when a singular case is studied, any generalizations must await further support from other studies (Leedy and Ormond, 2010). This does limit the impact of performing a singular cases study, but does not discount the viability of information gleaned from the case. By contrast, Yamashita and Moonan argue there is also a difficulty when using multiple case studies. There is a potential bias in selecting multiple cases (Yamashita and Moonan, 2014). An opportunity to skew data and pick like cases can cause inferences which are not necessary reflective of the whole body of work. In any case, the reader must assimilate multiple sources to develop a picture of a situation through the case or cases. The researcher's responsibility is to meld the sources and information together creating an overarching understanding of the case(s). For this paper, the review of the AM data presented should allow the reader to reach a similar conclusion.

Proof of Concept Methodology

A proof of concept, also referred as a proof of principle, is the realization of a certain method or idea to demonstrate its feasibility, or a demonstration in principle, whose purpose is to verify that some concept or theory has the potential of being used (Information Technology Guideline, 2010). A proof of concept can be a beginning step, middle step or the last step before a decision to adopt a technology or solution. It is an important step to gauge whether the proposed technology or solution meets the determined set of requirements. According to Weaver and French, this method has the ability to functionally test a solution, determine how the test subject performs within the environment, and the interaction of the subject with other capabilities of the system (Information Technology Guideline, 2010). The goal is to gain experience with the solution or technology, determine if it is viable and a practical approach for your organizational needs. Vogt point out, it is difficult to "prove" anything with research as all information is interpreted (Vogt, 2007). However, Weaver and French conclude this method is vital in cases where a measurement and observation of performance is preferred, while not investing or the overall organization by adopting the technology or solution. A review of literature determined an abundance of proof of concept (proof of principle) methodology use in technology and medical research.

Additive Manufacturing Case Study and Proof of Concept

To approach the initial AM investigative question posed, a methodical approach was implemented. First, define the subject of study. The research and literature review narrowed the focus to a case study. Initially, the paper honed in on the metal powders and AM processes, as there is an abundance of metals such as titanium, aluminum and steel on aircraft. However, the research quickly determined this AM technology at the tactical level is developmental. The DOD has initiatives to determine implementation at strategic levels such as DARPA research projects, NAVAIR testing and AFRL, but the circumstance preclude the use of the metal technology at the MXG level. Therefore, the research focused on the mature AM practices in plastics. This redirect, narrowed the scope of parts capable to be manufactured to phenolic, plastics and some composites. On any given aircraft, there are a large number of the parts consisting of these materials. Further research determined the 552d Maintenance Squadron (MXS) purchased a 3D printer and were on the cusp of certifying an E-3 AWACs seat cover piece made from a thermoplastic known as ULTEM 9085. This material was manufactured by the company Stratasys and certified for use on aircraft. It was determined to focus the case study on this operation.

The case study was retrospective in nature. It analyzed the process to field the 3D printer with the 552d MXS, how the AM process matured from the initial stages to the movement towards additional applications. The study sought to measure the impacts of manning, training, time and money associated with the process. The use of the 3D printer expanded for the 552d MXG as expected. The first “breakthrough” occurred when posed the problem with manufacturing E-3 AWACs leading edge bleed air duct brackets (Green, 2016). These brackets are designed to secure the bleed air ducts running under the skin along the leading edge of the wing (Figure 10). The solution involved making a part for the aircraft, but no an AM part. The importance of this part of the case study is how the unit merged AM and subtractive methods to produce tooling to support aircraft operations.

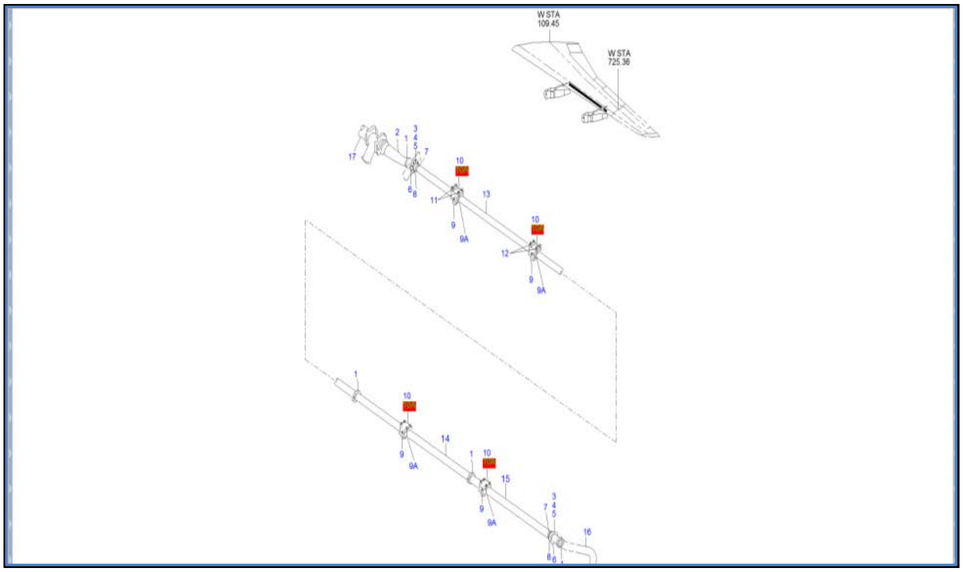


Figure 10. E-3 Leading Edge, Bleed Air Duct

The 552d MXS, Fabrication Flight observed a difficult problem with manufacturing the replacement leading edge brackets for the aircraft (McBride, 2016). During the isochronal inspection, E-3's were averaging four cracked brackets on the leading edge (Figure 11). During the past calendar year, the flight had ordered or manufactured 138 brackets for use on the fleet. Research of the supply system identified the cost of each bracket was $4,000 which would cost the unit $552,000 annually. Having the option to manufacture (due to the lack of parts in the system and high demand), the sheet metal technician would make, by hand, the brackets using cutters, benders and drills. This process took 8 man-hours per bracket (Green, 2016). The man-hour cost from for one hour of a sheet metal technician's time from FSS Manpower was quote as $46.25 for the purpose of the research (Green, 2016). The cost of the materials to produce the bracket was $10 each. The total cost to produce one bracket was $380 with an annual cost of $52,440.

Figure 11. E-3 Environmental Duct Leading Edge Bracket

Tangible cost aside, the problem faced by the flight entailed the amount of hours required to manufacture the brackets. Averaging four brackets, with an ETIC of 8 hours per bracket, the cost in man-hours alone was 40 hours per isochronal inspection. The annual manpower cost to manufacture the brackets was 1,360 man-hours. This had a ripple effect within the flight. Unable to keep up with normal operational demands, the flight decided to bring in technicians on the weekend to manufacture the brackets (Green, 2016). The weekend duty supplemented the normal weekend duty schedule, in essence doubling the weekend coverage. This work schedule for the shop had become normal operations.

Additionally, the E-3 aircraft in isochronal inspection had not made an on-time output from the inspection, being 100% late for the programmed time. The efforts by the flight to bring personnel in on the weekends and to manufacture the parts locally, did mitigate further delays; however, the flight sought other solutions.

The second initiative sought by the 552d MXG, was to explore the use of ULTEM 9085 as a replacement of honeycomb and phenolic. Flight controls on aircraft consist of honeycombed aluminum, which give strength in conjunction with decreased weight. To replace damage, the Air Force used honeycomb made from phenolic or fiberglass. This honeycomb is difficult to work for a variety of reasons.

The phenolic honeycomb is quite flexible. This flexibility makes the process of machining it difficult (McBride, 2016). In lieu of machining, the only option was to grind it to fit, which produced varying levels of accuracy. Another difficulty observed is the thickness of the repair for the flight control. Some thicknesses require the phenolic to be stacked up three sheets thick, which requires cutting and stacking of the material. Historically, this is a long process which can take up to 5 days of 24 hours shifts to manufacture (Green, 2016). The manufactured piece is stacked using alternating layers of potting compound which is time consuming. The flight highlighted the most striking problem with phenolic honeycomb repair, it is highly hazardous. The fiberglass repair pieces are carcinogenic and posed a health risk to personnel handling the material in particulate form.

Additionally, the overall research used some prospective research techniques, by using the proof of concept to identify and print a new part from another airframe and organization. The nature of the study employed both an illustrated and exploratory effort. Illustrated techniques assists in "painting the picture" (Yamashita, 2014), to understand where 3D printing might be employed within an MXG. It allows for the reader to assimilate the information. To assist conveying the information, exploratory factors such as choosing to print a part using another airframe further solidifies the intent of the case study. The goal of the research is to provide an overall case of MXG's 3D printing operations to produce recommendations and guide leadership decisions based on evidence.

To fulfill the research goal, the strategy simply consisted of answering the investigative questions. To reach that goal, it was determined a vital step was to observe the 3D printing operation and perform interviews with the shareholders. The on-site collection of data consisted of 3D printer equipment specifications, the materials qualities and meeting of product specifications. Following the site visit, additional data collection occurred with Internet research, library research, interviewing experts, and other fieldwork to include visits to NAVAIR and DARPA.

After the core research, the focus changed to determine which airframe would be chosen for the proof of concept. First, the research sought to determine what aircraft in the Air Force inventory would benefit from a proof of concept with 3D printing. To encompass both legacy and modern Air Force airframes, the C-130 was selected. The C-130 has a long line history and variants dating back to the initial delivery in August 1952 to the modern C-130J. Additionally, the widespread use of the airframe within the Total Force is an additional attribute. The C-130 airframe has parts manufactured from the earlier variants to the C-130J which are virtually the same on all models.

The C-130J Aft Cargo Door Rub Strip was the part selected for manufacture using the 3D printer (Figure 12 and 13). The material to make the rub strip is normally phenolic. It was determined, through the case study, that ULTEM 9085 could replace phenolic, but it still required an engineering disposition. To test the process of another MXG to utilize the AM process, the research honed in on the 86th MXS GO81 historical and technical data. Selecting the part entailed some important criteria. First, was the part non-procurable? Although this selected part can be ordered, it is also permitted for manufacture if the rub strip is not available in supply. GO81 data identified two rub strips over the past 5 years were ordered and not filled by supply. This required the 86th MXS to manufacture the part out of phenolic stock. Contributing to some limitations in manufacturing the past, the lack of C-130J source, maintenance, recovery codes required extra research into technical data (00-25-195, 2012).

The proof of concept continued with accessing the Air Force Engineering and Technical Services (AFETS) database to procure technical drawings to manufacture the part. Once the specifications were obtained, the drawings were sent electronically to the 552d MXS where a technician converted the drawing into a .stl file. This process of drawing the part used FeatureCam or SolidWorks is CAD software found on CNC machines (McBride, 2016). It took the technician approximately five minute to draw the specifications for the rub strip. Once the .stl file was imported into the 3D printer, the internal INSIGHT software sliced the file into pieces to convert the image for the 3D printer. The internal file in the 3D printer became a .cmd file for the printer to use. Once the 3D printer began to manufacture the rub strip, it took 61 minutes to complete, by full automation requiring zero manpower to monitor the manufacturing process. The material used was 2.55 inches^3 of ULTEM 9085 and 0.2 inches^3 of ULTEM support material. The total cost of the printed part was $26.33. The cost to order the part via supply would cost $36.23.

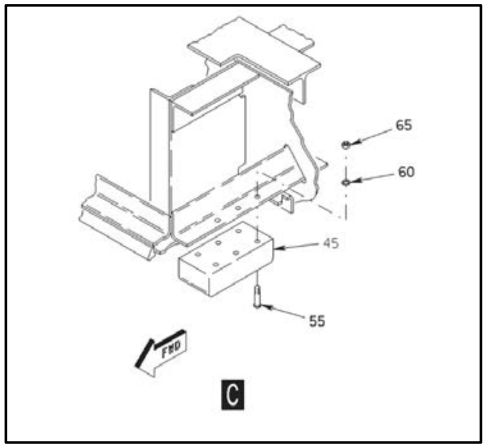


Figure 12. C-130J Aft Cargo Door Rub Strip Drawing

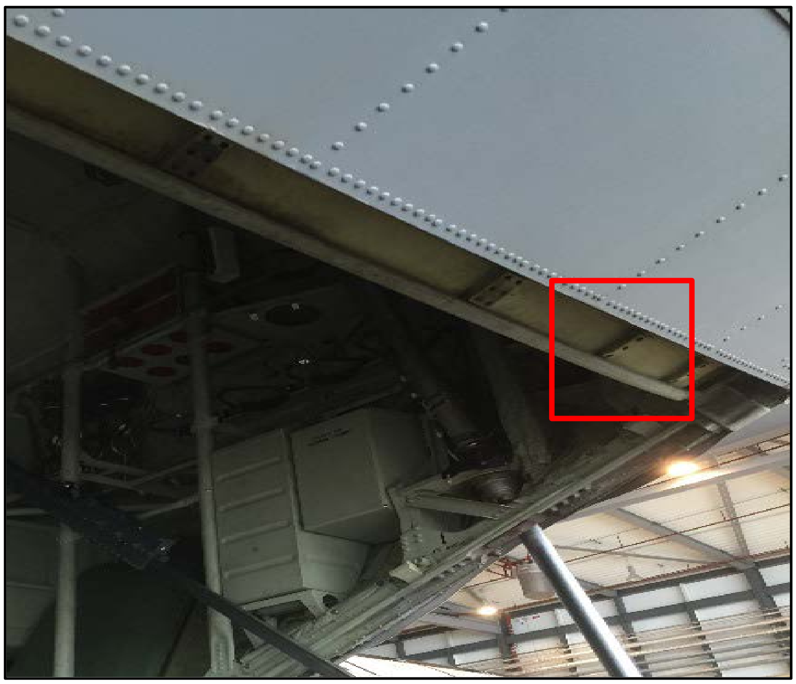


Figure 13. C-130J Aft Cargo Door Rub Strip

Summary

The combination of a case study and proof of concept is one way to present the potential attributes for AM within the aircraft maintenance community. The potential to produce aircraft parts and tooling is evident in the research, and presents an opportunity for leaders and stakeholders to determine if there is enough qualitative data to adopt this technology across the aircraft maintenance community. The 552d MXG's use of the 3D printer to produce tooling and parts was stunning. The ability to translate the case study's lesson and apply them to the proof of principle produced a viable C-130J Aft Cargo Door Rub Strip. The following chapter will analyze the results of the case study and proof of concept. It is expected, a review of both the case study and proof of principle will provide recommendations for further study or adoption of the technology is warranted.

IV. Analysis and Results

Chapter Overview

This chapter focused on interpreting the data obtained by both the case study and proof of concept. The analysis began with developing the case study for the 552d MXG, Tinker AFB, OK and evaluating how their use of a 3D printer impacted their maintenance operation. After careful consideration and research, the application of their part selection method and AM methodology was applied to the search for a part from another airframe and a different MXG. The result was the proof of concept resulting in the identification and 3D printing of the C-130J Aft Cargo Door Rub Strip from the 86th MXG, Ramstein AB, GE. This chapter summarizes the results.

Results of Case Study

The original analysis for the case study was the 552d MXG's solution to use the 3D printer to manufacture tooling. As stated, the overall problem consisted of three fundamental parts.

First, the research highlighted, to purchase 138 E-3 bleed air duct brackets from the supply system, it would cost the unit $4,000 each or $552,000 annually. This method was not practical as the parts were non-procurable due to the high demand and lack of parts in the system. The unit chose to locally manufacture the bleed air duct brackets for an annual cost of $52,440 using traditional methods. This created a savings of $499,560 or a 90% decrease in the cost to manufacture locally than to procure it through supply. However, the problem still existed in exchanging the aforementioned cost savings by losing 1,360 man-hours annually to manufacture 139 brackets annually (8 man-hours to manufacture one bracket). This cost affected the flight's morale and manning crunch (Green, 2016). The flight embarked upon the next phase, by employing the 3D printer to begin modernizing their process.

The flight needed to create the bleed air brackets quickly to recoup time. To meet this goal, it was determined to utilize the new waterjet capability. The waterjet utilizes a water steam to cut materials, including metals. The waterjet, using a computer based CAD, would allow for rapid manufacturing of "blanks" in the shape of the bleed air brackets. The next phase was to minimize the hand-forming from the technician. The solution to that problem was provided by the 3D printer. Using the CNC software and the 3D printer, a mold was printed out of ULTEM 9085. This consisted of two parts, the base and the form (Figures 14 and 15). The unit used the base and form to bend the metal blanks into the shape of the bleed air bracket on a press. The result were immediately beneficial and the process was simple. The bleed air brackets are programmed and cut on the waterjet, stamped out with the mold (20 at a time by a technician) and assembled into serviceable parts (Figure 16). The form allowed for a streamlined manufacturing process cutting a bleed air bracket's overall assembly time from 8 man-hours to 1.5 man-hours. It was and 81.25% decrease in man-hours. The original savings of $499,560 to manufacture, combined with the waterjet and 3D process saved the man-hour 1,035 man-hours.

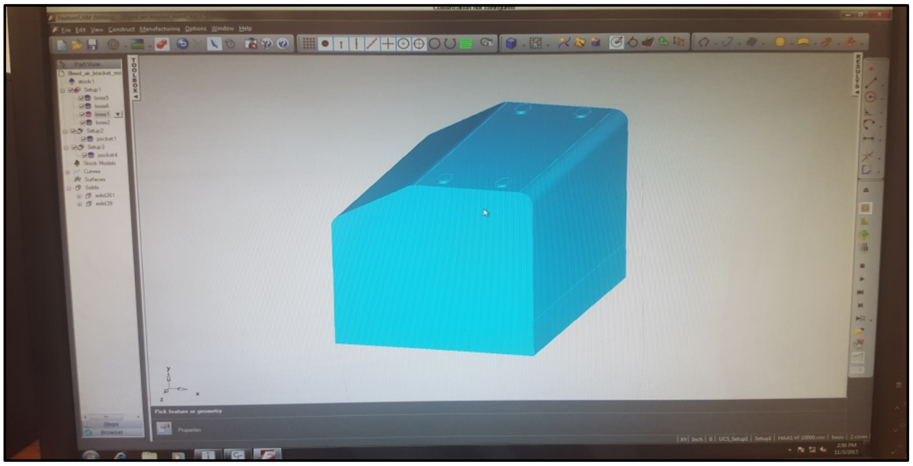


Figure 14. 3D Printed Mold Base, Bleed Air Duct Bracket

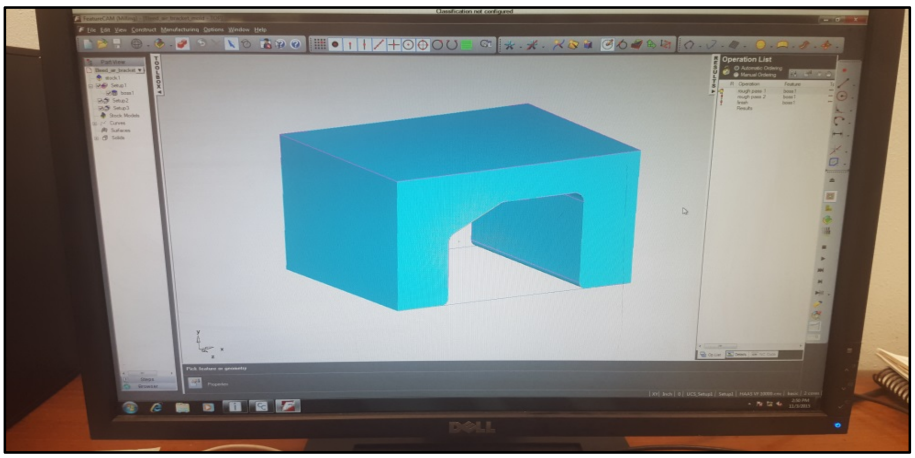


Figure 15. 3D Printed Mold Form, Bleed Air Duct Bracket

The process also enables the rapid manufacture of the parts and repeatable, minimizing reject rates and rework. The technicians could manufacture multiple parts during one session. The result of this process created a supply surplus for the unit. The unit manufactured parts that were turned in under the stock number to meet supply requirements on-base and throughout the Air Force. With the savings in time, the unit eliminated the extra weekend duty requirement. This allowed flight leadership more management and flexibility for their flight positively impacting morale (Green, 2016).

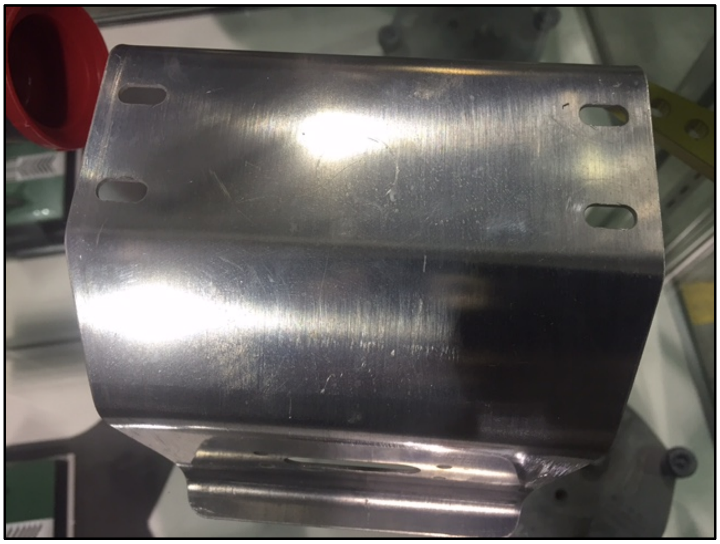


Figure 16. Molded Bleed Air Duct Bracket

The cost to 3D print the mold was $890 of ULTEM 9085. The manpower cost with the reduced man-hours from 8 hours to 1.5 hours per bracket decreased to $9,573.72. The total investment with the new AM methodology, lower man-hours and the mold was estimated to cost $$11,843.75 if the unit needed to produce 138 bracket in future years. This further reduced the cost of this manufacturing process by 77%.

It was apparent the AM technology impacted the ability to produce a tool that enabled a cost savings in manpower and material. The next aspect of the case study, built upon using AM manufactured parts. During the research, the Air Force authorized the use of the E-3 AWACs seat cover made from ULTEM 9085. This result invigorated the effort to seek the use of ULTEM 9085 as a replacement of the honeycomb and phenolic. The benefits to replace the honeycomb and phenolic material with ULTEM 9085 start with the elimination of the exposure to carcinogens. Although proper personal protection equipment is used, the complete elimination of personal hazards would be the optimal situation. The fiberglass nature of the honeycomb material inherently has the risk of exposure to fiberglass. Comparatively, ULTEM 9085 does not produce carcinogenic hazardous like phenolic. Due to the cutting of the phenolic, the particles are introduced into the atmosphere. ULTEM 9085 is in solid form when handling the material. The exposure to hazards is virtually eliminated. The hazardous material also precludes the use of systems such as the waterjet. Using the waterjet would introduce hazardous materials into the water, creating a waste stream requiring costly disposal.

The repairs used with the replacement honeycomb consists of cutting out the damaged flight control area (Figure 17), then manufacturing the honeycomb to produce a replacement core and smooth outer shell. As stated in the earlier research, this could take days to fabricate, keeping an airframe in a non-mission capable status. For the repair indicated in Figure 16, the process would take 48 hours to complete. By contrast, the 3D printer can print the exact replica of the honeycomb structure out of ULTEM 9085 (Figure 18).   The process to 3D print the honeycomb would take 10 minutes to design on the computer and 10 hours to manufacture on the FDM 3D printer. The overall repair time would take no more than 24 hours, eliminating 24 hours of downtime.   The 3D printing does not required manpower to manufacture the part, the technician would be released to work additional taskers while the 3D printer makes the custom honeycomb part. The benefit of point-of use is demonstrated from this portion of the case study. Related back to the AFFOC, *A View of the Air Force in 2035*, "acquisition and logistics enterprise that is capable of rapidly identifying, acquiring, and fielding solutions through organic additive manufacturing or commercial off-the-shelf sources" would allow for immediate delivery of a part.

Figure 17. Flight Control Repair

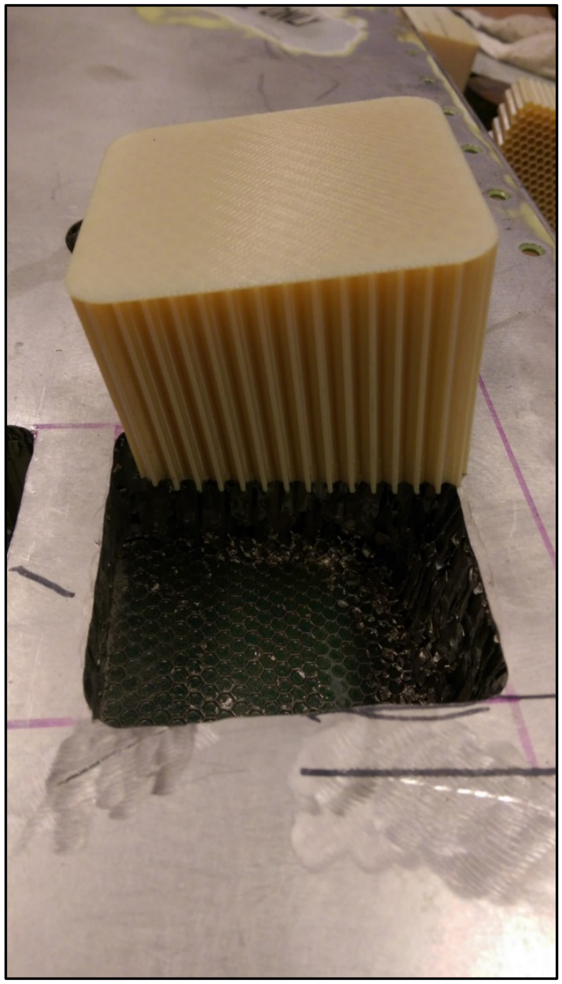


Figure 18. 3D Printed ULTEM 9085 Honeycomb

The prototyping effort demonstrated the 552d MXG created an opportunity to challenge conventional logistics and manufacturing. The case study showed there are viable uses of 3D printers for the use at the MXG level. Specifically, the use of the FDM-based industrial 3D printer from Stratasys has not only the capability to print aircraft parts, but the material that is certified for use on both FAA and DOD governed aircraft.

Results of Proof of Concept

The proof of concept completed and rounded out the study. The product produced was exceptional. After selecting the C-130J Aft Cargo Door Rub Strip and the 552d MXG 3D printer, the results of the printed part speaks for itself (Figures 19 - 21).

The part was manufactured with the six holes premanufactured. No post manufacturing modifications were required. The part met the specification of the original drawings. The part was not installed on the aircraft. The process to seek approval to permanently utilize this 3D printing method, the specific part design and material approval is underway. If permitted, the part's drawing currently exists and in rapid form, would be printed in 61 minutes if required. The total cost of the printed part was $26.33 versus $36.23, a savings of 27%. Difficult to factor, the shipping time required for the part to be procured from CONUS and shipped to Germany. A conservative estimate is 72 hours to work through supply, transportation and customs clearance. The 3D printed part would be available approximately 61 minutes after notification to the metals technology shop.

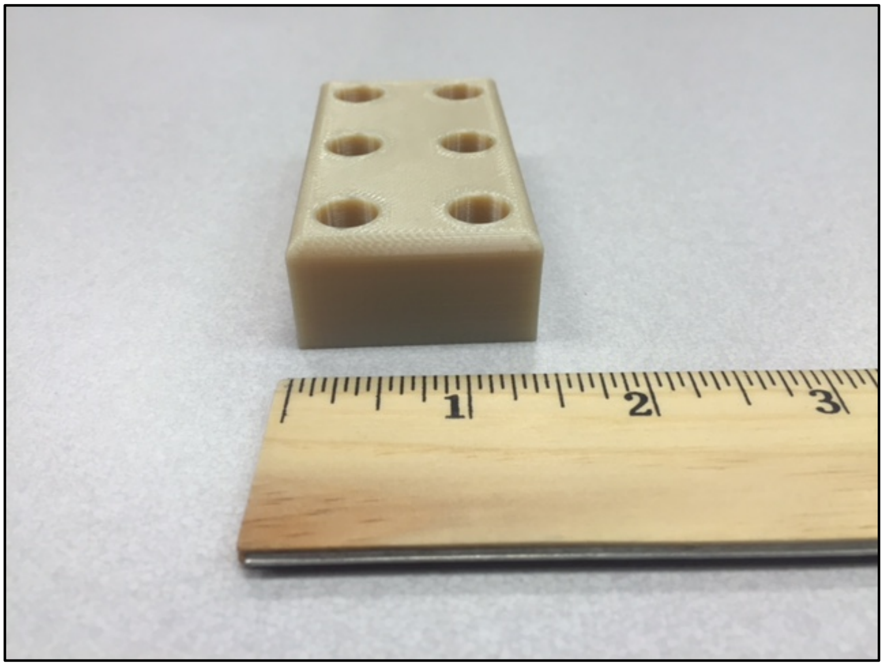


Figure 19. End View, 3D Printed C-130J Aft Cargo Door Rub Strip

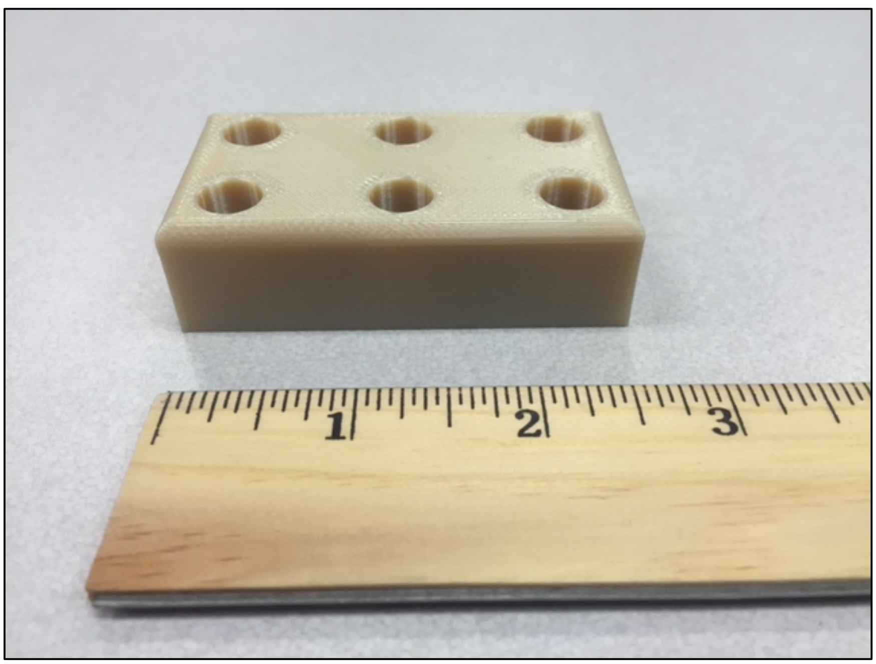


Figure 20. Side View, 3D Printed C-130J Aft Cargo Door Rub Strip

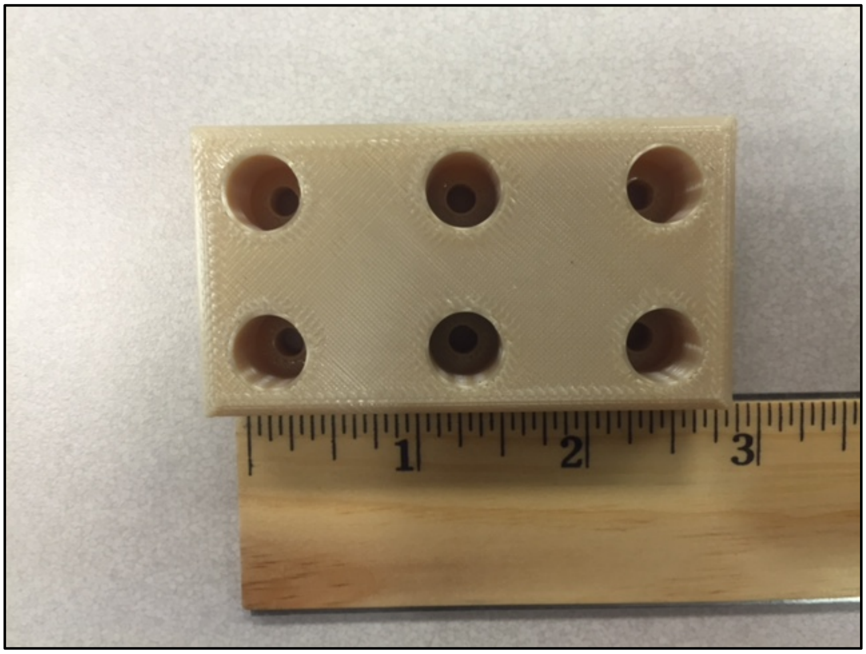


Figure 21. Top view, 3D Printed C-130J Aft Cargo Door Rub Strip

Investigative Questions Answered

The first investigative question posed was: Is AM technology mature enough to warrant adoption at the MXG level to produce viable aircraft components? The case study determined this to be true through the analysis of the 552d MXS AM practices. In January 2016, the E-3 AWACS seat end caps were certified for operational use on aircraft. This groundbreaking event, removed barriers within the Air Force aircraft maintenance community to produce AM parts. The part is minimal and considered a secondary part (if not cosmetic in nature), but does enable two import factors. First, the use of the thermoplastic material ULTEM 9085. A COT material meets the Air Force's engineering standards for aircraft use. Secondly, the validation of current 3D printers using FDM methodology can impact the current Air Force supply chain and provide hard to procure parts for the aircraft maintenance community.

The case study and proof of concept showed, through manufacturing of three parts, the impact 3D printing can have on the aircraft maintenance community. First, from a tooling perspective, the 3D printer can provide innovative solutions to traditional manufacturing at the MXG level. Secondly, the use of 3D printer to produce plastic parts for modern and legacy aircraft which are non-procurable is a valued asset both in cost and manpower. Finally, the capacity to challenge the manufacturing, supply chain and engineering aspects of parts procurement by producing viable alternative to the manufacturing of aircraft parts..

The proof of concept was designed to answer the second question "can a proof of concept be made to print an aircraft part?" The C-130J Aft Cargo Door Rub Strip is a viable aircraft part, printed to the exact specifications of the drawing and made of material equivalent to the original phenolic. Further engineering disposition is required for use, but the proof of concept determined the capability of producing a 3D part on another airframe from another MXG.

Summary

This chapter analyzed the results of both the case study and proof of concept. The impacts of 3D printers on the MXG are clearly defined in the research. Form aircraft parts to tooling, the FDM-based 3D printer has the capacity to impact how aircraft maintenance units produce parts, supplement their manufacturing techniques, manage personnel and ultimately return aircraft back to mission capable status quicker.

V. Conclusions and Recommendations

Conclusions of Research

Through a case study and proof of principle, it was determined the Air Force's aircraft maintenance community can benefit from current AM technology. Specifically, the fielding of 3D printers for MXG level use is viable and should be implemented.

To answer "if AM technology is mature enough to warrant adoption at the MXG level to produce aircraft parts", the Air Force needs to take a holistic view of aircraft part manufacturing. The current AM technology to produce secondary and tertiary aircraft parts exists; however more research and reliability testing for advanced metals and composites must mature before MXG implementation. The use of FDM materials such as ULTEM 9085, researched by OEMs and certified for use on aircraft, demonstrated during the research the viability of using COT technology. The benefit of this course of action, places the research and certification process on the OEM to produce material and technology worthy for aircraft use. The purchase of COT 3D printers, reinforces the logistics vision stated in AFFOC, *A View of the Air Force in 2035*. (AFFOC, 2015), demonstrated the applicability of fielding a 3D printer to manufacture parts at the tactical level. Once implemented at the MXG level, the process to produce aircraft parts and seek approval for use will commence. The value is the immediate point-of-use for aircraft technicians to quickly manufacture parts in a safe and timely manner.

Furthermore, the use of AM technology would support MXG's prototyping effort, local tool manufacturing and augmentation of current subtractive manufacturing methods. Each aforementioned application has the capacity to save time, money, and increase aircraft availability. No matter if the airframe is decades old or recently off the manufacturing line, the supply chain is diverse and dynamic. Parts availability, especially non-critical parts, can become difficult to procure. The use of FDM-based 3D printers are not only viable, but necessary to change the landscape of aircraft parts manufacturing and procurement. The 552d MXG, driven by the vision and innovation of a group of Noncommissioned Officers, realized the practical application of 3D printing in today's aircraft maintenance community.

Significance of Research

At the onset of this research, the objective was to introduce AM technology to the aircraft maintenance community. Specifically, the ultimate vision was to identify AM technology using metals. However, this goal was not in line with the two original research questions posed, "is AM technology mature enough to warrant adoption at the MXG level to produce aircraft parts" and "can a proof of concept be made to print an aircraft part." At the conclusion of this research, it was determined the ability to field AM technology, specifically FDM-based 3D printers at the MXG level, can provide cost benefit, manpower savings and increase aircraft availability for an MXG. Additionally, expanding the number of 3D printers available to MXGs will produce the similar savings and would enable the evolution of the use of AM technology at the tactical aircraft maintenance level.

Recommendations for Action

This research should serve as a starting point for leaders to adopt 3D printers for use at the MXG level. During the recent fiscal constrains targeting the DOD, the implementation of innovative, COT technology can save in both manpower and cost, while increasing mission readiness. Although the use of FDM-based 3D printers would support only aircraft parts based in plastics and phenolic, there are ample parts utilized on aircraft made from these materials and it would begin the transformation of logistics support toward the future vision of a dynamic and agile supply chain. Expansion of the 3D printer's use to non-aircraft related tasks at a particular wing would provide additional capabilities to all wings.

The research demonstrated that AM technology is viable and can bridge the gap for difficult to procure parts which are normally tied up in acquisition processes or logistics sourcing issues. Thermoplastic parts, derived from 3D printers, have an application for use in the current aircraft maintenance community. With significant savings for any MAJCOM to implement, the aircraft maintenance community should invest in 3D printer suites to produce the thermoplastic parts for modern and legacy airframes. The focus of the 3D printer's use should begin with support of secondary aircraft structures and cosmetic items, tooling prototyping of parts and supplementation of current subtractive manufacturing techniques. However, unforeseen manufacturing applications would be expected from the tactical level once implemented.

Recommendations for Future Research

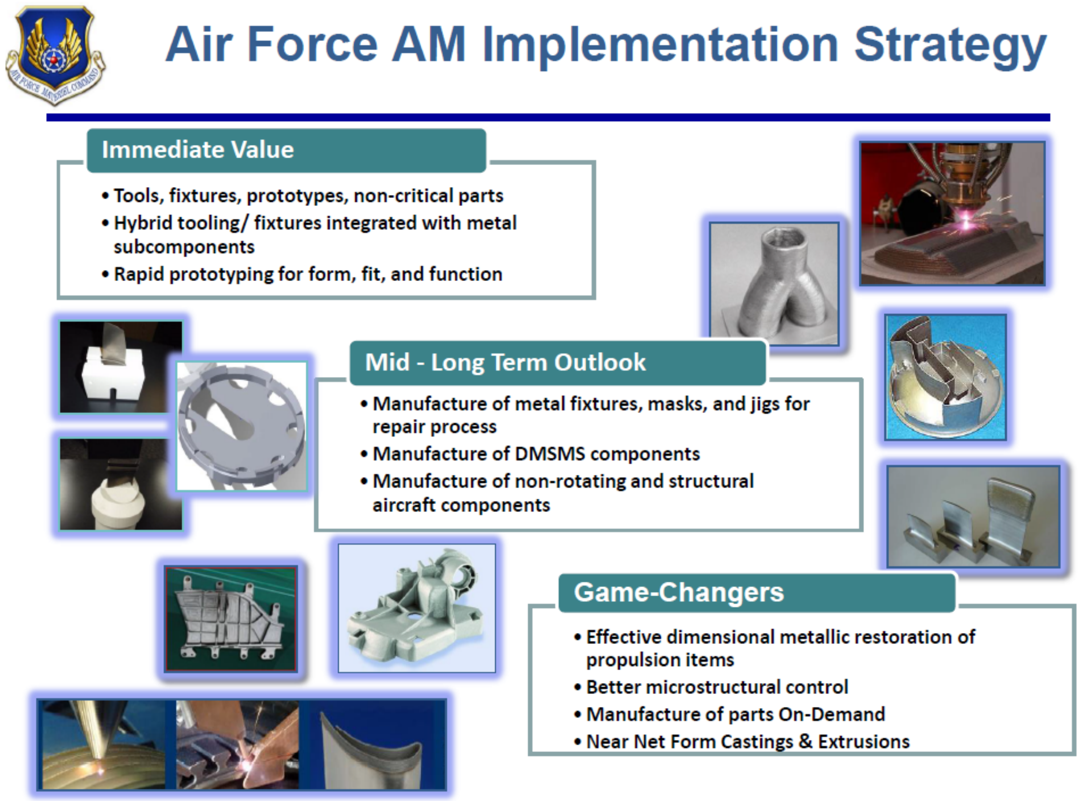
The AM arena offers rich opportunities for further research. The constant innovation and evolution of AM technology can make this current study obsolete in a relatively short period of time. The limits of this specific research paper beckon for additional analysis in this subject matter, focused on more quantitative analysis and modeling. To close the gap on Air Force capabilities, further research into the other AM manufacturing techniques would provide more data to examine adoption of other AM methods within aircraft maintenance.

A study focused on AM as an optional method for aircraft temporary repair actions and Aircraft Battle Damage Repair have operational impact. Acquiring the ability to 3D print parts to return aircraft back to limited operational status has merit and an immediate operational impact. It is strongly suggested to partner with industry and researchers to analyze the metallurgical properties of the material used within AM. This specific research would drive important analysis in reliability and maintainability standards and data. Finally, expanding the scope of the research to apply AM methodology to any Air Force discipline, specifically at the tactical level, would bring beneficial results to the overall Air Force.

Summary

The aircraft supply chain network is incapable, at times, of procuring some aircraft in a timely and efficient manner. The lack of parts and the subsequent production of non-procurable aircraft parts affect each major aircraft weapons system. The Air Force aircraft maintenance community stands to gain considerable agility in the logistics and supply chains by implementing FDM-based 3D printers for use at the MXG level. By applying the AM technology, aircraft maintenance leaders will save in cost savings, manpower, time, and airframe availability. The logistics and supply chains of the future will use 3D printers (AFFOC, 2015). The time to utilize this technology starts now.

Appendix A: Air Force AM Implementation Strategy



Appendix B: ULTEM 9085 Properties

THERMAL PROPERTIES[3]	TEST METHOD	ENGLISH	METRIC
Heat Deflection (HDT) @ 264 psi, 0.125" unannealed	ASTM D648	307°F	153°C
Glass Transition Temperature (Tg)	DSC (SSYS)	367°F	186°C
Coefficient of Thermal Expansion	ASTM E831	3.67×10^{-05} in/(in·°F)	65.27 μm/(m·°C)
Melting Point	---------------	Not Applicable[3]	Not Applicable[3]

MECHANICAL PROPERTIES[1]	TEST METHOD	ENGLISH		METRIC	
		XZ ORIENTATION	ZX ORIENTATION	XZ ORIENTATION	ZX ORIENTATION
Tensile Strength, Yield (Type 1, 0.125", 0.2"/min)	ASTM D638	6,600 psi	4,800 psi	47 MPa	33 MPa
Tensile Strength, Ultimate (Type 1, 0.125", 0.2"/min)	ASTM D638	9,950 psi	6,100 psi	69 MPa	42 MPa
Tensile Modulus (Type 1, 0.125", 0.2"/min)	ASTM D638	312,000 psi	329,000 psi	2,150 MPa	2,270 MPa
Tensile Elongation at Break (Type 1, 0.125", 0.2"/min)	ASTM D638	5.8%	2.2%	5.8%	2.2%
Tensile Elongation at Yield (Type 1, 0.125", 0.2"/min)	ASTM D638	2.2%	1.7%	2.2%	1.7%
Flexural Strength (Method 1, 0.05"/min)	ASTM D790	16,200 psi	9,900 psi	112 MPa	68 MPa
Flexural Modulus (Method 1, 0.05"/min)	ASTM D790	331,000 psi	297,000 psi	2,300 MPa	2,050 MPa
Flexural Strain at Break (Method 1, 0.05"/min)	ASTM D790	No break	3.7%	No break	3.7%
IZOD Impact, notched (Method A, 23°C)	ASTM D256	2.2 ft-lb/in	0.9 ft-lb/in	120 J/m	48 J/m
IZOD Impact, un-notched (Method A, 23°C)	ASTM D256	14.6 ft-lb/in	3.2 ft-lb/in	781 J/m	172 J/m
Compressive Strength, Yield (Method 1, 0.05"/min)	ASTM D695	14,500 psi	12,700 psi	100 MPa	87 MPa
Compressive Strength, Ultimate (Method 1, 0.05"/min)	ASTM D695	26,200 psi	13,100 psi	181 MPa	90 MPa
Compressive Modulus (Method 1, 0.05"/min)	ASTM D695	1,030,000 psi	251,000 psi	7,012 MPa	1,731 MPa

ELECTRICAL PROPERTIES	TEST METHOD	VALUE RANGE
Volume Resistivity	ASTM D257	4.9×10^{15} - 8.2×10^{15} ohm-cm
Dielectric Constant	ASTM D150-98	3 - 3.2
Dissipation Factor	ASTM D150-98	.0026 - .0027
Dielectric Strength	ASTM D149-09, Method A	110 - 290 V/mil

OTHER[2]	TEST METHOD	VALUE
Specific Gravity	ASTM D792	1.34
Rockwell Hardness	ASTM D785	---
Flame Classification	UL94	V-0 (1.5 mm, 3 mm)
Oxygen Index	ASTM D2863	0.49
OSU Total Heat Release (2 min test, . 060" thick)	FAR 25.853	16 kW min/m²
UL File Number	---------------	E345258
Outgassing		
Total Mass Loss (TML)	ASTM E595	0.41% (1.00% maximum)
Collected Volatile Condensable Material (CVCM)	ASTM E595	-0.1% (0.10% maximum)
Water Vapor Recovered (WVR)	ASTM E595	-0.37% (report)
Fungus Resistance (Method 508.6)	MIL-STD-810G	Passed
Burn Testing		
Horizontal Burn (15 sec)	14 CFR/FAR 25.853	Passed (0.060" thick)
Vertical Burn (60 sec)	14 CFR/FAR 25.853	Passed (0.060" thick)
Vertical Burn (12 sec)	14 CFR/FAR 25.853	Passed (0.060" thick)
45° Ignition	14 CFR/FAR 25.853	Passed (0.060" thick)
Heat Release	14 CFR/FAR 25.853	Passed (0.060" thick)
NBS Smoke Density (flaming)	ASTM F814/E662	Passed (0.060" thick)
NBS Smoke Density (non-flaming)	ASTM F814/E662	Passed (0.060" thick)

Appendix C: Usable on Codes

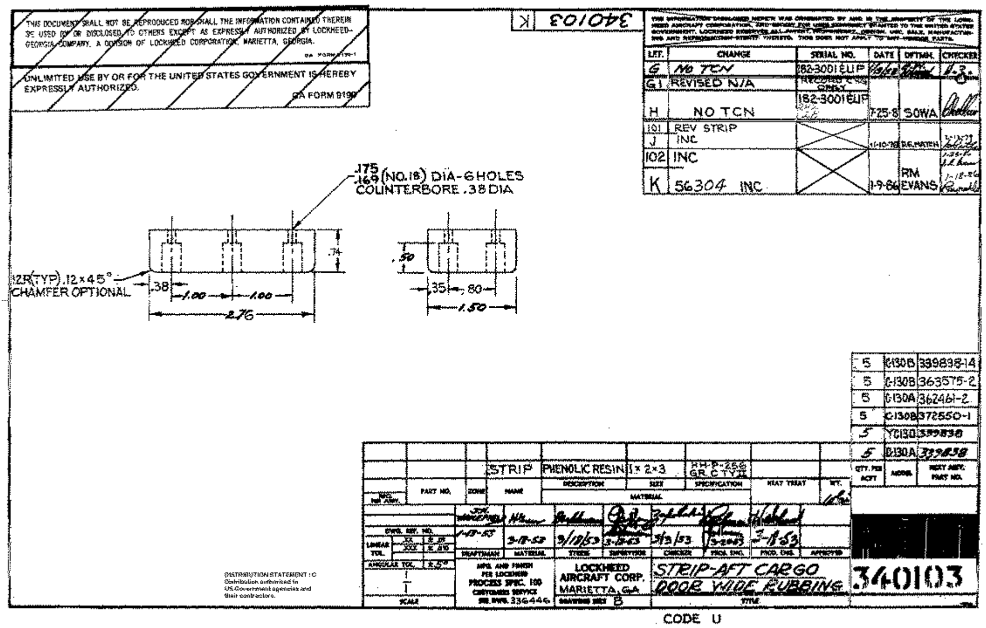
TO 1C-130J-4-52-1 TO 1C-130J-4-52-1

FIG. ITEM	PART NUMBER	CAGE	DESCRIPTION 1 2 3 4 5 6 7	USABLE ON CODE	UNITS PER ASSY	
13A			CARGO DOOR (FIGURE 2 OF 3)			
- 5	3356962-9	98897	DOOR ASSY, AFT CARGO (WHEN EXHAUSTED USE 3358848-1) (SEE 52-30-00 FIG. 11 FOR NHA AND ADDITIONAL DETAILS) (REWORKED AND REIDENTIFIED FROM 3352543-1)	A	REF	
- 5	3358848-1	98897	DOOR ASSY, AFT CARGO (PREFERRED SPARE IN LIEU OF 3356962-9) (SEE 52-30-00 FIG. 11 FOR NHA AND ADDITIONAL DETAILS) (WHEN EXHAUSTED USE 3358848-3)	B	REF	R
- 5	3358848-3	98897	DOOR ASSY, AFT CARGO (PREFERRED SPARE IN LIEU OF 3356962-9, 3358848-1) (SEE 52-30-00 FIG. 11 FOR NHA AND ADDITIONAL DETAILS)	B	REF	R
- 5	3356962-7	98897	DOOR ASSY, AFT CARGO (SEE 52-30-00 FIG. 11 FOR NHA AND ADDITIONAL DETAILS) (REWORKED AND REIDENTIFIED FROM 3352877-1)	C	REF	
- 10	368562-1	98897	. BULKHEAD INSTL, FRONT, AFT CARGO DOOR	C	NP	
- 10	3352546-1	98897	. BULKHEAD INSTL, FRONT, AFT CARGO DOOR	B	NP	
- 15	368562-3	98897	. . BULKHEAD ASSY, FRONT, AFT CARGO DOOR	C	1	
- 15	3352545-1	98897	. . BULKHEAD ASSY, FRONT, AFT CARGO DOOR	B	NP	
- 16	373081-1L	98897	. . . SUPPORT, DOOR LATCH, AFT CARGO DOOR		1	
- 17	373081-1R	98897	. . . SUPPORT, DOOR LATCH, AFT CARGO DOOR		1	
25	373080-2	98897	. . . CHANNEL, LATCH, AFT CARGO DOOR SUPPORT		2	
30	NAS517-3-4	80205	. . . SCREW (AP)		4	
35	LS35307-3M	98897	. . . WASHER (AP)		4	
40	MS21042-3	96906	. . . NUT (AP)		4	
45	340103	98897	. . . STRIP, WIDE RUBBING, AFT CARGO DOOR		5	
50	340104	98897	. . . STRIP, NARROW RUBBING, AFT CARGO DOOR		4	
55	NAS623-2-6	80205	. . . SCREW		42	
60	NAS1149FN816P	80205	. . . WASHER		42	
65	MS21042-08	96906	. . . NUT		42	
- 68	368558-1	98897	. . . LATCH ASSY, AFT CARGO DOOR		2	
70	368559-1	98897	. . . . PIN ASSY, LATCH, AFT CARGO DOOR		1	
75	NAS562-8-8A	80205	. . . . CAM FOLLOWER		1	
80	373956-1	98897	. . . PLATE, LATCH, AFT CARGO DOOR		2	
85	NAS517-4-9	80205	. . . SCREW (AP)		2	
90	NAS517-4-7	80205	. . . SCREW (AP)		6	
95	MS21299-4	96906	. . . WASHER (AP)		8	
100	MS21042-4	96906	. . . NUT (AP)		8	
-105	373111-11	98897	. INSULATION INSTL, AFT CARGO DOOR	B	NP	
-105	373111-13	98897	. INSULATION INSTL, AFT CARGO DOOR	C	NP	
110	373111-15	98897	. . INSULATION, AFT CARGO DOOR	C	1	
115	373113-1	98897	. . INSULATION, AFT CARGO DOOR CHAMFERED		2	
120	373113-2	98897	. . INSULATION, AFT CARGO DOOR CHAMFERED		2	
125	373113-3	98897	. . INSULATION, AFT CARGO DOOR		4	
130	375935-1	98897	. . INSULATION, AFT CARGO DOOR RECTANGULAR, NOTCHED CORNER		1	
135	375935-2	98897	. . INSULATION, AFT CARGO DOOR RECTANGULAR, NOTCHED CORNER		1	
140	373113-300	98897	. . INSULATION, AFT CARGO DOOR CHAMFERED		2	
145	373114-1	98897	. . INSULATION, AFT CARGO DOOR RECTANGULAR		1	
150	373114-2	98897	. . INSULATION, AFT CARGO DOOR RECTANGULAR		2	
155	373114-3	98897	. . INSULATION, AFT CARGO DOOR RECTANGULAR		2	
160	373114-4	98897	. . INSULATION, AFT CARGO DOOR RECTANGULAR		2	
165	373114-5	98897	. . INSULATION, AFT CARGO DOOR RECTANGULAR		1	
170	373114-7	98897	. . INSULATION, AFT CARGO DOOR		2	
175	373114-9	98897	. . INSULATION, AFT CARGO DOOR	C	2	
180	373114-300	98897	. . INSULATION, AFT CARGO DOOR RECTANGULAR	B	1	
-185	371629-1L	98897	. HINGE ASSY, AFT CARGO DOOR		1	
-200	371629-1R	98897	. HINGE ASSY, AFT CARGO DOOR		1	

- ITEM NOT ILLUSTRATED

52-30-00
13A-4
JAN 01/16
Change 8

Appendix D: C-130J Rub Strip



SUBMITTED UNDER CONTRACT
F33657-82-C-2110
FSCM 98897

Appendix E: Quad Chart

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Vita

Major Michael J. Thompson graduated from Madison Area Memorial High School in Madison, Maine. He entered Active Duty as an Airman Basic July 1990 as a Strategic Air Command Electro-Environmental Systems Specialist. He graduated with a Bachelor of Science in Education and Training from Wayland Baptist University 2001 and was commissioned through Officer Training School at Maxwell AFB, Alabama. He earned a Masters of Art in Military History from American Military University in 2010.

Major Thompson's first aircraft maintenance officer assignment was McGuire AFB, NJ serving in both the 305th Maintenance Group (MXG) and 816th Air Mobility Squadron. Next, he was assigned to the 5th MXG at Minot AFB, ND where he served as Officer-in-Charge, Quality Assurance and the Special Weapons Flight Commander. The following assignment was Squadron Officer College (SOC), Maxwell AFB, AL as an Instructor, Director of Training and ADO. He was selected to attend the Advanced Maintenance and Munitions Officer School, Nellis AFB, NV in 2009. Furthermore, he deployed on a 365 day deployment to Baghdad, Iraq to serve as an Air Advisor during Operation New Dawn in 2011. Finally, he served as a Maintenance Operations Officer for both the 86th Maintenance Squadron (MXS) and the 86th Aircraft Maintenance Squadron before becoming the Commander for the 86th MXS.

In May 2015, Maj Thompson entered the Advanced Study of Air Mobility at the Air Force Expeditionary Center, JB MDL, New Jersey, to complete his Intermediate Developmental Education. Upon graduation, he will take command of the 727th Special Operations Aircraft Maintenance Squadron Cannon AFB, NM.

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14. ABSTRACT The purpose of this research was to evaluate the effectiveness of additive manufacturing (AM) or 3D printing for the Air Force aircraft maintenance community and determine if the technology is applicable at the Maintenance Group (MXG) level. Specifically, this paper sought to answer one pivotal question, addressing if AM is mature enough to produce viable aircraft components for use and if so, prove the concept by printing an aircraft part for operational use. Research uncovered the 552d MXG at Tinker AFB efforts to create difficult to procure aircraft parts and tooling using a 3D printer. A case study of the 552d MXG's 3D printing operation explores their use of a Fused Deposition Modeling (FDM) thermoplastic material to manufacture parts at the squadron level. This paper also explored recent innovations and methodologies used in AM within the aerospace industry. The research continued by applying the case study's analysis toward a proof of concept, producing a C-130J Aft Cargo Door Rub Strip for 3D printing. The study concluded by presenting Air Mobility Command's (AMC) leadership with a recommendation to field 3D printing suites for AMC units to leverage additive manufacturing as an alternate source for aircraft parts and tooling.						
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